

METHODS FOR TREATING MULTIPLE SCLEROSIS**RELATED APPLICATIONS**

This application claims the benefit of priority under 35 U.S.C. 119(e) to co-pending U.S. Provisional Application No(s). 60/103,742, filed on October 9, 1998, the entire contents of which is hereby incorporated by reference.

BACKGROUND OF THE INVENTION

Deprenyl (also referred to herein as selegiline or R-(-)-N, α -Dimethyl-N-2-propynyl phenethylamine) was first used as an adjunct to conventional drug therapy (L-dihydroxyphenylalanine (L-DOPA) plus a peripheral decarboxylase inhibitor) of Parkinson's disease (PD) in Europe over a decade ago on the basis that as a selective monoamine oxidase-B (MAO-B) inhibitor, it would elevate brain dopamine levels and potentiate the pharmacological action of dopamine formed from L-DOPA, and yet prevent the tyramine-pressor effect observed with non-selective MAO inhibitors. The combined drug therapy was reported to prolong the anti-akinetic effects of L-DOPA, resulting in the disappearance of on-off effects, reduced functional disability, and increased life-expectancy in PD patients (Bernheimer, H., et al., J. Neurolog. Sci., 1973. 20: 415-455, Birkmayer, W., et al., J. Neural Transm., 1975. 36:303-336, Birkmayer, W., et al., Mod. Prob. Pharmacopsychiatr., 1983. 19: 170-177, Birkmayer, W. and P. Riederer, Hassler, R.G. and J.F. Christ (Ed.) Advances In Neurology, 1984. 40(Y): p.0-89004, and Birkmayer, W., et al., J. Neural Transm., 1985. 64(2): p. 113-128).

Studies examining deprenyl as an adjunct to conventional L-DOPA therapy have reported a short term benefit which was usually lost by 1 year or less. Some, but not all, have reported that the levodopa dose can be decreased when taken in conjunction with deprenyl (Elizan, T.S., et al., Arch Neurol, 1989. 46(12): p. 1280-1283, Fischer, P.A. and H. Baas, J. Neural Transm. (suppl.), 1987. 25: p. 137-147, Golbe, L.I., Neurology, 1989. 39: p. 1109-1111, Lieberman, A.N. et al., N.Y. State J. Med., 1987. 87: p. 646-649, Poewe, W., F. Gerstenbrand, and G. Ransomayr, J. Neural Transm. (suppl.), 1987. 25: p. 137-147, Cedarbaum, J.M., M. Hoey, and F.H. McDowell, J. Neurol. Neurosurg. Psychiatry, 1989. 52(2): p. 207-212, and Golbe, L.I., J.W. Langston, and I. Shoulson, Drugs, 1990. 39(5): p. 646-651).

Increasingly, deprenyl is being administered to Parkinson's disease patients following reports (Parkinson, S.G. Arch Neurol 46, 1052-1060 (1989) and U.S.A., Parkinson, S.G. N. Engl. J. Med. 321, 1364-1371 (1989)) that it delays the disease progression; a mechanism has recently been proposed to explain its action (See, e.g., Tatton & Redman 1996).

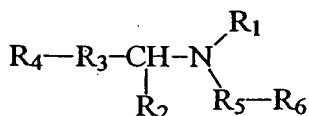
SUMMARY OF THE INVENTION

It has now been discovered that certain compounds are capable of increasing survival of oligodendrocytes. The invention provides methods for increasing survival of oligodendrocytes

both *in vivo* and *in vitro*, of preventing or inhibiting death of oligodendrocytes, of preventing or inhibiting the progression of Multiple Sclerosis, and methods for treating Multiple Sclerosis.

In one aspect, the invention provides a method for increasing survival of oligodendrocytes. The method comprises administering to a subject in need thereof an effective amount of a deprenyl compound such that survival of oligodendrocytes is increased.

5 In certain embodiments, the deprenyl compound is represented by the structure:



in which

10 R₁ is hydrogen, alkyl, alkenyl, alkynyl, aralkyl, alkylcarbonyl, arylcarbonyl, alkoxy carbonyl, or aryloxy carbonyl;

R₂ is hydrogen or alkyl;

R₃ is a single bond, alkylene, or -(CH₂)_n-X-(CH₂)_m;

in which X is O, S, or N-methyl; m is 1 or 2; and n is 0, 1, or 2;

R₄ is alkyl, alkenyl, alkynyl, heterocyclic, aryl or aralkyl; and

15 R₅ is alkylene, alkenylene, alkynylene and alkoxyethylene; and

R₆ is C₃-C₆ cycloalkyl or

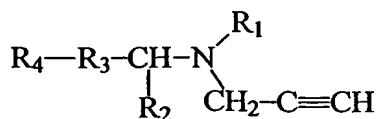


R₂ and R₄-R₃ are joined to form, together with the methine to which they are attached, a cyclic or polycyclic group;

20 and pharmaceutically acceptable salts thereof. In certain embodiments: R₁ is a group that can be removed *in vivo*; R₁ is hydrogen; R₁ is alkyl; R₁ is methyl; R₂ is methyl; R₃ is methylene; wherein R₄ is aryl; R₄ is phenyl; R₅ is methylene; R₆ is



25 In certain preferred embodiments, the deprenyl compound is represented by the structure:



in which

R₁ is hydrogen, alkyl, alkenyl, alkynyl, aralkyl, alkylcarbonyl, arylcarbonyl, alkoxy carbonyl, or aryloxy carbonyl;

R₂ is hydrogen or alkyl;

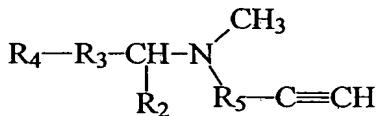
5 R₃ is a bond or methylene; and

R₄ is aryl or aralkyl; or

R₂ and R₄-R₃ are joined to form, together with the methine to which they are attached, a cyclic or polycyclic group;

and pharmaceutically acceptable salts thereof.

10 In certain preferred embodiments, the deprenyl compound is represented by the structure:



in which

R₂ is hydrogen or alkyl;

15 R₃ is a bond or methylene; and

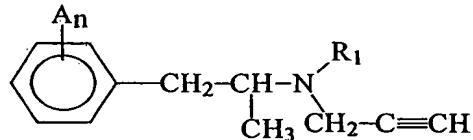
R₄ is aryl or aralkyl; or

R₂ and R₄-R₃ are joined to form, together with the methine to which they are attached, a cyclic or polycyclic group; and

R₅ is alkylene, alkenylene, alkynylene and alkoxylen;

20 and pharmaceutically acceptable salts thereof.

In certain preferred embodiments, the deprenyl compound is represented by the structure:



in which

25 R₁ is hydrogen, alkyl, alkenyl, alkynyl, aralkyl, alkylcarbonyl, arylcarbonyl, alkoxy carbonyl, or aryloxy carbonyl;

A is a substituent independently selected for each occurrence from the group consisting of halogen, hydroxyl, alkyl, alkoxy, cyano, nitro, amino, carboxyl, -CF₃, or azido;

n is 0 or an integer from 1 to 5;

and pharmaceutically acceptable salts thereof.

5 In certain preferred embodiments, the patient is a human. In a particularly preferred embodiment, the deprenyl compound is (-)-desmethyldeprenyl.

In another aspect, the invention provides a method for inhibiting Multiple Sclerosis, comprising administering to a patient an effective amount of a deprenyl compound such that 10 Multiple Sclerosis is inhibited. In a preferred embodiment, the deprenyl compound is (-)-desmethyldeprenyl. In certain embodiments, the patient is a human.

In another aspect, the invention provides a method for increasing oligodendrocyte survival *in vitro*, comprising contacting oligodendrocytes with an effective amount of a deprenyl compound such that oligodendrocyte survival is increased.

In another aspect, the invention provides a method for increasing oligodendrocyte 15 survival in a patient, comprising contacting a oligodendrocyte with a deprenyl compound such that oligodendrocyte survival increases. In preferred embodiments, the patient is a human; the deprenyl compound is (-)-desmethyldeprenyl; and/or the (-)-desmethyldeprenyl is administered transdermally to the patient.

BRIEF DESCRIPTION OF THE DRAWING

20 **Fig. 1:** Progressive maturation of oligodendrocytes *in vitro*. Phase-contrast microphotographs of oligodendrocytes after 12 (A), 13 (B), 14 (C) and 16 days (D) of culture. 0-2A progenitor cells isolated from postnatal day 2 rat cortex were grown in a chemically defined media supplemented with insulin (5 11g/ml) and IGF-I (2.5 ng/ml). Bipolar 0-2As (A) differentiate into multipolar PROLs (B, C) which develop into OLs (D) bearing an extensive network of 25 branching processes. The cell marked by the white arrow in A is a typical 0-2A while typical multiprocessed PROLs are shown in (B) and (C) marked by white arrows. The white arrow in panel (D) marks a typical example of an OL. A 16 DIV culture constituted about 2% 0-2As, 32% PROLs and 62% OLs and 4%AST.

Fig. 2: Immunocytochemical characterization of the cells of the oligodendroglial lineage. 0-2A 30 progenitors on 12 days *in vitro* (DIV) were labeled with an antibody to a surface tetraganglioside A2B5 (A). PROLs express CNP (B) and GC (C) on 13 DIV. OLs on 16 DIV reacted with anti-MBP (D) and anti-PLP protein (E) antibodies. Note MBP expression in the cell body and processes. An intense staining of PLP was found in the cell body. AST was identified by staining with an antibody to GFAP (F). GFAP positive ASTs show reticulated 35 somal areas.

Fig. 3: Withdrawal of insulin and IGF-I decreases the number of intact nuclei and intact cells. (-)-Deprenyl increased the survival of oligodendrocytes in a serum free, insulin and IGF-I deprived base medium (BM). After 16 DIV, cells were washed and incubated in BM or BM supplemented with 10^{-9} M (-)-deprenyl (BM-D9) for 24h. For controls, washed cells were replaced in media (IM) containing insulin (5 μ g/ml) and IGF-I (2.5ng/ml) or IM supplemented with 10^{-9} M (-)-deprenyl (IM-D9). Intact nuclei were counted using a haemocytometer after Zap-oglobin lysis. Total cell numbers indicate counts of intact methylene blue stained cells by a random method (see Materials and Methods). Data shown are mean percentage + SEM of nuclei (A1, A2) or cells (B1, B2) relative to IM counted in two experimental series in which the cells were grown at seeding densities of 5.3×10^3 cells/cm² (experimental series - I) and 15.8×10^3 cells/cm² (experimental series - II).

Fig. 4: Morphological identification of the oligodendroglial cells identified by methylene blue staining. 0-2As exhibit a typical bipolar morphology with two long thin processes extending from the cell body (A) while the PROL show a multipolar appearance with 3-5 processes (B). A complex network of secondary and tertiary processes branching off form the primary process characterizes OLs (C). AST display a flattened morphology with a larger cell body and nucleus compared to 0-2As, PROLs and OLs (D).

Fig. 5: Effects of insulin and IGF-I withdrawal and treatment with R(-)-deprenyl on oligodendroglial cell numbers. Cells grown on coverslips on 16 DIV were incubated in BM, BM-D9, IM or IM-D9 for 24 hours. After the treatment period cells were stained with 1% methylene blue solution containing 1% AgNO₃. Methylene blue stained positive cell types were morphologically identified as 0-2As, PROLs, OLs or AST and counted in 25 randomly chosen 100 power fields on triplicate coverslips. Results are expressed as mean + SEM of experiments series - I (A) and experimental series -II (B).

Fig. 6: Insulin and IGF-I withdrawn oligodendrocytes display fragmented process morphology. Cells at 16 DIV were washed and replaced in IM or BM. Panels show transmitted light microscopic images of cells incubated in IM (A1) or in BM (B 1) for 18h. Cells were subsequently fixed in 4% paraformaldehyde and stained with an antibody to myelin basic protein (MBP). Panels (A2) and (B2) are interference contrast micrographs of MBP positive OLs. Note the extensively branched processes of OLs incubated in IM (A1, A2). Cells placed in BM show fragmented processes but display an intact cell body (B 1, B2).

Fig. 7: Apoptosis of PROLs and OLs on IGF-I and insulin withdrawal. Panel (A) shows the internucleosomal DNA degradation of PROLs and OLs. DNA "ladders" showing internucleosomal DNA digestion can be observed when cells were placed in BM for 18 h after washing. The ladder pattern is not seen when cells were incubated in IM or BM-D9. Panel (B) shows the nuclear DNA cleavage of apoptotic oligodendrocytes. Insulin and IGF-I withdrawn

cells were stained for free 3' ends of cut DNA using the Apop Tag™ method (see Materials and Methods). Inset in panel (B) shows apoptotic OLs. The apoptotic nuclei typically show pyknosis and DNA fragmentation. Panel (C) shows an interference contrast micrograph of an apoptotic OL, as revealed by the Apop Tag method, displaying shrinkage of the cell body and fragmentation of processes. Panels (D 1) and (D2) show fluorescence photomicrographs of PROLs and OLs deprived of insulin and IGF-I for 18 hours and stained with Hoechst 33258. Apoptotic cells show bright, condensed chromatin (open arrows) while non-apoptotic cells show nuclei with diffuse and granular pattern of staining (white arrows). Panel (D1) also shows an intensely fluorescent lobular structure (empty arrow) characteristic of an apoptotic body.

Fig. 8: Time course of apoptotic death of PROLs and OLs. Oligodendroglial cultures grown on coverslips at 16 DIV were incubated in IM/BM/BM-D9 or IM-D9 for 6, 12, 15, 18 and 24 h. Staining of fragmented nuclear DNA in OLs was performed using the Apop Tag method (see Materials and Methods). Apop Tag positive nuclei were counted in 25 randomly chosen 100 power fields on triplicate coverslips. Data from experimental series I and II (A and B) are expressed as mean number + SEM of apoptotic nuclei / mm². Note the occurrence of apoptotic nuclei after 6h of trophic withdrawal, peaking at 18 h. (-)-Deprenyl reduced the incidence of apoptotic nuclei at all the time points after IGF-I and insulin withdrawal.

Fig. 9: Concentration-survival relationship on treatment with S (+) and R (-) - deprenyl.
After 16 DIV, cells were washed and incubated in BM or BM with 10⁻⁵M, 10⁻⁷M and 10⁻⁹M, S (+) or R (-)-deprenyl for 24h. For controls, washed cells were replaced in IM. Intact nuclei were counted using a hemocytometer after Zap-oglobin lysis (see Materials and Methods). Data shown are mean percentage ± SEM of intact nuclei relative to IM.

Fig. 10: Effects of insulin/IGF-I withdrawal and anti-apoptotic compounds on oligodendroglial protein levels. Total protein extracted from the cells placed in BM, IM, BM-D9/BM-Ds9 or IM-D9 for 18h after washing. Western blot analysis of the proteins was performed and the blots were probed with antibodies to MBP, CNP, GC and PLP. MBP, CNP and GC show decreased immunodensity when placed in BM. (-)-Deprenyl as well as (-)-desmethyldeprenyl markedly increased the immunodensity of the proteins.

Fig. 11: Effects of general cytochrome P450 blockers on (-)-deprenyl and (-)-desmethyldeprenyl induced changes in OL cell survival. OLs grown on glass coverslips were incubated in BM supplemented with 10⁻⁹ M (-)-deprenyl or (-)-desmethyldeprenyl and treated with the general cytochrome P450 blockers proadifen, metapyrone, or piperonyl butoxide for 24h. Cells were also treated with (-)-methamphetamine or (-)-amphetamine alone in BM or with 10⁻⁹ M (-)-deprenyl or (-)-desmethyldeprenyl. Concentrations of the P450 blockers as well as of (-)-methamphetamine or (-)-amphetamine are indicated above the respective bars. Intact

nuclei were counted on a haemocytometer following Zap-oglobin lysis. Control cells were washed and incubated in IM. Data shown represent the mean percentage of intact nuclei \pm SEM relative to IM.

Fig. 12: Reduction of oligodendroglial apoptosis by (-)-desmethyldeprenyl is protein synthesis dependent. After 16 DIV, cells were washed and incubated in BM, BM-Ds9 or BM-Ds9 plus the translation or transcription blockers cycloheximide or actinomycin respectively.

Concentrations of cycloheximide and actinomycin are indicated above the respective bars.

Intact nuclei were counted on a hemocytometer following Zap-oglobin lysis. Control cells were washed and incubated in IM. Data shown represent the mean percentage of intact nuclei \pm SEM relative to IM.

Fig. 13: Effects of IGF-I and insulin withdrawal on mitochondrial membrane potential ($\Delta\psi_M$) of oligodendroglial lineage cells. Cells grown on glass coverslips were incubated in IM (A) or BM (B) for 18h, and then incubated with the potentiometric dye CMTMR (138 nM) for 15 min at 37°C before fixation with 4% paraformaldehyde on ice for 30 min. Confocal images with

constant power and pinhole aperture settings were obtained of each cell type, ASTs, PROLs, OLs. A minimum of 20 images were obtained for each cell type. Using the image acquisition and analysis software Metamorph™, 2 regions within an individual mitochondrion were selected and the fluorescence intensity was measured on a scale of 0-255. No fewer than 20 such regions were measured from each cell. The distribution of CMTMR fluorescence intensity observed in each cell type is shown and the mean intensity \pm SD is given. Note the higher percentage of mitochondria in ASTs with low CMTMR fluorescence intensity compared to PROLs and OLs grown in IM. Also note the shift to the left in the distribution of CMTMR fluorescence intensity in each cell type when incubated in BM, indicating a reduction in $\Delta\psi_M$. OLs and PROLs have a high proportion of mitochondria with relatively high level $\Delta\psi_M$.

Fig. 14: Effects of (-)-deprenyl and (-)-desmethyldeprenyl on $\Delta\psi_M$ of oligodendroglial lineage cells. Cells grown on glass coverslips were incubated in BM-D9 (A) or BM-Ds9 (B) for 18h and stained with CMTMR as before followed by fixation with 4% paraformaldehyde. Confocal images were obtained with constant power and pinhole aperture settings of ASTs, PROLs and ASTs. CMTMR fluorescence intensity values were obtained as described using the Metamorph image analysis software from 20 individual mitochondria within 20 cells. Values are the mean \pm SD intensity of CMTMR fluorescence. Also shown are frequency distributions of mitochondrial CMTMR fluorescence in each treatment. Note that both (-)-deprenyl and (-)-desmethyldeprenyl prevented the decrease in $\Delta\psi_M$.

Fig. 15: Effects of general cytochrome P450 blockers on (-)-deprenyl and (-)-desmethyldeprenyl induced changes in $\Delta\psi_M$. OLs grown on glass coverslips were incubated in BM supplemented with 10⁻⁹M (-)-deprenyl or (-)-desmethyldeprenyl and treated with the

general cytochrome P450 blockers proadifen, metapyrone, or piperonyl butoxide for 18h. At the end of the treatment period cells were incubated with CMTMR as before and fixed in 4% paraformaldehyde. Confocal images were obtained using constant power and pinhole aperture settings and CMTMR intensity was measured using the Metamorph image analysis software from 20 individual mitochondria within 20 cells per group. Values represent the mean \pm SD intensity of CMTMR fluorescence. The frequency distributions of mitochondrial CMTMR fluorescence are also shown. Note that treatment with general cytochrome P450 blockers prevented the maintenance of $\Delta\psi_M$ provided by (-)-deprenyl but not by (-)-desmethyldeprenyl, indicating that metabolism of (-)-deprenyl to (-)-desmethyldeprenyl is necessary for its protective effects.

Fig. 16: Effects of (-)-methamphetamine and (-)-amphetamine on (-)-deprenyl and (-)-desmethyldeprenyl induced changes in $\Delta\psi_M$ of oligodendroglial cells. OLs grown on glass coverslips were incubated in BM for 18h supplemented with 10^{-9} M (-)-deprenyl or (-)-desmethyldeprenyl and treated with 10^{-5} M (-)-methamphetamine or 10^{-5} M (-)-amphetamine. Cells were incubated with CMTMR as described and fixed in 4% paraformaldehyde. Confocal images were obtained using constant power and pinhole aperutre settings of a minimum of 20 cells per group. CMTMR fluorescence intensity was measured using the Metamorph™ image analysis software from a minimum of 20 individual mitochondria in each cell. Values represent the mean \pm SD intensity of CMTMR fluorescence. The frequency distributions of mitochondrial CMTMR fluorescence are also shown. Note that the addition of (-)-methamphetamine or (-)-amphetamine to cells incubated in BM supplemented with (-)-deprenyl or (-)-desmethyldeprenyl prevented the maintenance of $\Delta\psi_M$ provided by both (-)-deprenyl and (-)-desmethyldeprenyl.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides methods for increasing oligodendrocyte survival in a patient or *in vitro*, or for treating Multiple Sclerosis in a subject suffering from, or susceptible to, Multiple Sclerosis.

The terms "patient" or "subject", as used herein, refer to a warm-blooded animal having damaged glial and/or oligodendrocytes, or suffering from or susceptible to oligodendrocyte damage or death, or suffering from or susceptible to Multiple Sclerosis. In preferred embodiments, the patient is a mammal, including humans and non-human mammals such as dogs, cats, pigs, cows, sheep, goats, rats, and mice. In a particularly preferred embodiment, the patient is a human. In certain embodiments, the patient is suffering from a condition associated with Multiple Sclerosis, including, but not limited to, diabetes, AIDS, rheumatoid arthritis, or a thyroid disease. The methods of the invention are also useful for preventing or slowing the onset of Multiple Sclerosis or a symptom or condition associated therewith in a patient not yet suffering from Multiple Sclerosis, but susceptible to the development of Multiple Sclerosis.

Thus, prophylactic administration of a deprenyl compound can inhibit oligodendrocyte death or development of Multiple Sclerosis in a patient who would otherwise be susceptible to such a condition.

The term "rescue of damaged oligodendrocytes" or "rescuing of damaged glial cells" herein refer to the reversal of the sequence of damage to death in (otherwise) lethally damaged oligodendrocytes (or glial cells). In certain embodiments, "rescue of damaged oligodendrocytes includes prevention of apoptosis in a oligodendrocyte.

The language "increasing survival of oligodendrocytes" as used herein, refers to increasing numbers of oligodendrocytes, preventing death of oligodendrocytes, or otherwise 10 increasing numbers of oligodendrocytes (proliferating or non-proliferating), either *in vitro* (e.g., in cell culture) or in a subject.

The language "inhibiting Multiple Sclerosis" as used herein, refers to preventing, slowing or reversing the development of Multiple Sclerosis, or a symptom or condition associated therewith. For example, administration of a compound to a subject to inhibit 15 Multiple Sclerosis includes administering a compound such that progression of Multiple Sclerosis is prevented, slowed, or reversed, in whole or in part, or at least one symptom (or development of a symptom) is prevented, slowed, reversed, or otherwise ameliorated.

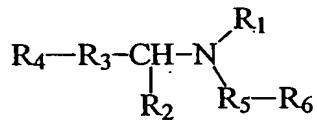
It is known that deprenyl and deprenyl compounds can rescue, or prevent the death of, damaged nerve cells (see, e.g., U.S. Patent No. 5,444,095 and International Publication No. 20 WO 97/28791, incorporated herein by reference). However, it is believed that the use of deprenyl or deprenyl compounds to increase the survival of oligodendrocytes, or to rescue, or prevent the death of, oligodendrocytes has not previously been reported.

The methods of the invention find use in treatment of conditions associated with Multiple Sclerosis, as well as in cell culture.

25 *I. Deprenyl Compounds*

The language "deprenyl compound", as used herein, includes deprenyl (N,α -dimethyl-N-2-propynylphenethylamine), compounds which are structurally similar to deprenyl, e.g., structural analogs, or derivatives thereof. Thus, in one embodiment, a deprenyl compound can be represented by the following formula (Formula I):

30



Formula I

in which

R₁ is hydrogen, alkyl, alkenyl, alkynyl, aralkyl, alkylcarbonyl, arylcarbonyl, alkoxy carbonyl, or aryloxycarbonyl;

R₂ is hydrogen or alkyl;

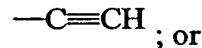
R₃ is a single bond, alkylene, or -(CH₂)_n-X-(CH₂)_m;

5 in which X is O, S, or N-methyl; m is 1 or 2; and n is 0, 1, or 2;

R₄ is alkyl, alkenyl, alkynyl, heterocyclyl, aryl or aralkyl; and

R₅ is alkylene, alkenylene, alkynylene and alkoxyethylene; and

R₆ is C₃-C₆ cycloalkyl or



10 R₂ and R₄-R₃ are joined to form, together with the methine to which they are attached, a cyclic or polycyclic group;

and pharmaceutically acceptable salts thereof.

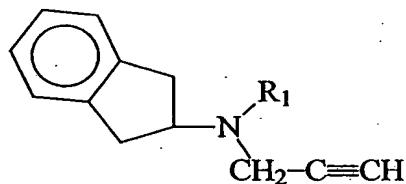
In certain preferred embodiments, a deprenyl compound is not selected from the group consisting of deprenyl, pargyline, AGN-1133, AGN-1135, or MD 240928.

15 In preferred embodiments, R₁ is a group that can be removed *in vivo*. In certain embodiments, R₁ is hydrogen. In other preferred embodiments, R₁ is methyl. In certain preferred embodiments, R₂ is hydrogen. In certain preferred embodiments, R₂ is methyl. In some preferred embodiments, R₃ is alkylene, more preferably methylene. In other preferred embodiments, R₃ is -(CH₂)_n-X-(CH₂)_m. In preferred embodiments, R₄ is aryl. In certain 20 preferred embodiments, R₄ is phenyl. In other preferred embodiments, R₄ is aralkyl. In yet other preferred embodiments, R₄ is alkyl. In still other preferred embodiments, R₅ is alkylene, more preferably methylene. In certain preferred embodiments, R₆ is

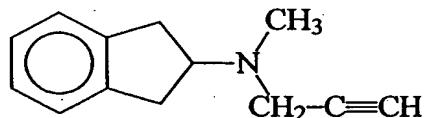


In other preferred embodiments, R₆ is cyclopentyl.

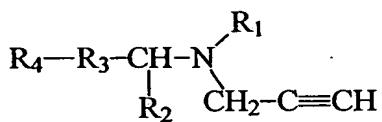
25 In another preferred embodiment, the deprenyl compound has the structure



wherein R₁ is as described above. Preferred deprenyl compounds include (-)-desmethyldeprenyl, and



In another embodiment, a deprenyl compound can be represented by the following formula (Formula II):



Formula II

in which

R_1 is hydrogen, alkyl, alkenyl, alkynyl, aralkyl, alkylcarbonyl, arylcarbonyl,

10 alkoxy carbonyl, or aryloxy carbonyl;

R_2 is hydrogen or alkyl;

R_3 is a bond or methylene; and

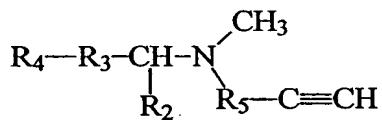
R_4 is aryl or aralkyl; or

R_2 and R_4-R_3 are joined to form, together with the methine to which they are attached,

15 a cyclic or polycyclic group;

and pharmaceutically acceptable salts thereof.

In another embodiment, the deprenyl compound can be represented by the following formula (Formula III):



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Formula III

in which

R_2 is hydrogen or alkyl;

R_3 is a bond or methylene; and

25 R_4 is aryl or aralkyl; or

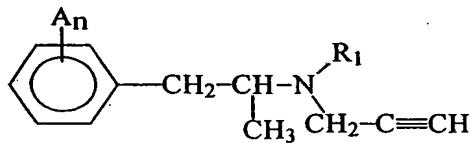
R_2 and R_4-R_3 are joined to form, together with the methine to which they are attached, a cyclic or polycyclic group; and

R_5 is alkylene, alkenylene, alkynylene and alkoxylen;

and pharmaceutically acceptable salts thereof.

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In yet another embodiment, the deprenyl compound can be represented by the following formula (Formula IV):



Formula IV

in which

- 5 R₁ is hydrogen, alkyl, alkenyl, alkynyl, aralkyl, alkylcarbonyl, arylcarbonyl, alkoxy carbonyl, or aryloxy carbonyl;
- A is a substituent independently selected for each occurrence from the group consisting of halogen, hydroxyl, alkyl, alkoxy, cyano, nitro, amino, carboxyl, -CF₃, or azido;
- 10 n is 0 or an integer from 1 to 5;
- and pharmaceutically acceptable salts thereof.

In certain embodiments of the invention, the deprenyl compound is not deprenyl (including (-)-deprenyl).

The term "alkyl" refers to the radical of saturated aliphatic groups, including straight-chain alkyl groups, branched-chain alkyl groups, cycloalkyl (alicyclic) groups, alkyl substituted cycloalkyl groups, and cycloalkyl substituted alkyl groups. In preferred embodiments, a straight chain or branched chain alkyl has 20 or fewer carbon atoms in its backbone (e.g., C₁-C₂₀ for straight chain, C₃-C₂₀ for branched chain), and more preferably 10 or fewer. Likewise, preferred cycloalkyls have from 4-10 carbon atoms in their ring structure, and more preferably have 5, 6 or 7 carbons in the ring structure. Unless the number of carbons is otherwise specified, "lower alkyl" as used herein means an alkyl group, as defined above, but having from one to six carbon atoms in its backbone structure. Likewise, "lower alkenyl" and "lower alkynyl" have similar chain lengths. Preferred alkyl groups are lower alkyls. In preferred embodiments, a substituent designated herein as alkyl is a lower alkyl.

Moreover, the term "alkyl" (or "lower alkyl") as used throughout the specification and claims is intended to include both "unsubstituted alkyls" and "substituted alkyls", the latter of which refers to alkyl moieties having substituents replacing a hydrogen on one or more carbons of the hydrocarbon backbone. Such substituents can include, for example, halogen, hydroxyl, carbonyl (such as carboxyl, ketones (including alkylcarbonyl and arylcarbonyl groups), and esters (including alkoxy carbonyl and aryloxy carbonyl groups)), thiocarbonyl, acyloxy, alkoxy, phosphoryl, phosphonate, phosphinate, amino, acylamino, amido, amidine, imino, cyano, nitro, azido, sulfhydryl, alkylthio, sulfate, sulfonate, sulfamoyl, sulfonamido, heterocyclyl, aralkyl, or an aromatic or heteroaromatic moiety. It will be understood by those skilled in the art that the moieties substituted on the hydrocarbon chain can themselves be substituted, if appropriate. For instance, the substituents of a substituted alkyl may include

substituted and unsubstituted forms of aminos, azidos, iminos, amidos, phosphoryls (including phosphonates and phosphinates), sulfonyls (including sulfates, sulfonamidos, sulfamoyls and sulfonates), and silyl groups, as well as ethers, alkylthios, carbonyls (including ketones, aldehydes, carboxylates, and esters), -CF₃, -CN and the like. Exemplary substituted alkyls are 5 described below. Cycloalkyls can be further substituted with alkyls, alkenyls, alkoxy, alkylthios, aminoalkyls, carbonyl-substituted alkyls, -CF₃, -CN, and the like.

The terms "alkenyl" and "alkynyl" refer to unsaturated aliphatic groups analogous in length and possible substitution to the alkyls described above, but that contain at least one double or triple bond respectively.

10 The term "aralkyl", as used herein, refers to an alkyl or alkenyl group substituted with at least one aryl group (e.g., an aromatic or heteroaromatic group). Exemplary aralkyls include benzyl (i.e., phenylmethyl), 2-naphthylethyl, 2-(2-pyridyl)propyl, 5-dibenzosuberyl, and the like.

15 The term "alkylcarbonyl", as used herein, refers to -C(O)-alkyl. Similarly, the term "arylcarbonyl" refers to -C(O)-aryl. The term "alkyloxycarbonyl", as used herein, refers to the group -C(O)-O-alkyl, and the term "aryloxycarbonyl" refers to -C(O)-O-aryl. The term "acyloxy" refers to -O-C(O)-R₇, in which R₇ is alkyl, alkenyl, alkynyl, aryl, aralkyl or heterocyclyl.

20 The term "amino", as used herein, refers to -N(R₈)(R₉), in which R₈ and R₉ are each independently hydrogen, alkyl, alkenyl, alkynyl, aralkyl, aryl, or R₈ and R₉, together with the nitrogen atom to which they are attached, form a ring having 4-8 atoms. Thus, the term "amino", as used herein, includes unsubstituted, monosubstituted (e.g., monoalkylamino or monoarylarnino), and disubstituted (e.g., dialkylamino or alkylarylarnino) amino groups. The term "amido" refers to -C(O)-N(R₈)(R₉), in which R₈ and R₉ are as defined above. The term 25 "acylamino" refers to -N(R'₈)C(O)-R₇, in which R₇ is as defined above and R'₈ is alkyl.

As used herein, the term "nitro" means -NO₂; the term "halogen" designates -F, -Cl, -Br or -I; the term "sulphydryl" means -SH; and the term "hydroxyl" means -OH.

30 The term "aryl" as used herein includes 5-, 6- and 7-membered aromatic groups that may include from zero to four heteroatoms in the ring, for example, phenyl, pyrrolyl, furyl, thiophenyl, imidazolyl, oxazole, thiazolyl, triazolyl, pyrazolyl, pyridyl, pyrazinyl, pyridazinyl and pyrimidinyl, and the like. Those aryl groups having heteroatoms in the ring structure may also be referred to as "aryl heterocycles" or "heteroaromatics". The aromatic ring can be substituted at one or more ring positions with such substituents as described above for alkyls, for example, halogen, azide, alkyl, aralkyl, alkenyl, alkynyl, cycloalkyl, hydroxyl, amino, nitro, 35 sulfhydryl, imino, amido, phosphonate, phosphinate, carbonyl, carboxyl, silyl, ether, alkylthio, sulfonyl, sulfonamido, ketone, aldehyde, ester, a heterocyclyl, an aromatic or heteroaromatic

moiety, $-CF_3$, $-CN$, or the like. Aryl groups can also be part of a polycyclic group. For example, aryl groups include fused aromatic moieties such as naphthyl, anthracenyl, quinolyl, indolyl, and the like.

The terms "heterocyclyl" or "heterocyclic group" refer to 4- to 10-membered ring structures, more preferably 4- to 7-membered rings, which ring structures include one to four heteroatoms. Heterocyclyl groups include, for example, pyrrolidine, oxolane, thiolane, imidazole, oxazole, piperidine, piperazine, morpholine, lactones, lactams such as azetidinones and pyrrolidinones, sultams, sultones, and the like. The heterocyclic ring can be substituted at one or more positions with such substituents as described above, as for example, halogen, alkyl, aralkyl, alkenyl, alkynyl, cycloalkyl, hydroxyl, amino, nitro, sulfhydryl, imino, amido, phosphonate, phosphinate, carbonyl, carboxyl, silyl, ether, alkylthio, sulfonyl, ketone, aldehyde, ester, a heterocyclyl, an aromatic or heteroaromatic moiety, $-CF_3$, $-CN$, or the like.

The terms "polycyclyl" or "polycyclic group" refer to two or more rings (e.g., cycloalkyls, cycloalkenyls, cycloalkynyls, aryls and/or heterocyclyls) in which two or more carbons are common to two adjoining rings, e.g., the rings are "fused rings". Rings that are joined through non-adjacent atoms are termed "bridged" rings. Each of the rings of the polycyclic group can be substituted with such substituents as described above, as for example, halogen, alkyl, aralkyl, alkenyl, alkynyl, cycloalkyl, hydroxyl, amino, nitro, sulfhydryl, imino, amido, phosphonate, phosphinate, carbonyl, carboxyl, silyl, ether, alkylthio, sulfonyl, ketone, aldehyde, ester, a heterocyclyl, an aromatic or heteroaromatic moiety, $-CF_3$, $-CN$, or the like.

The term "heteroatom" as used herein means an atom of any element other than carbon or hydrogen. Preferred heteroatoms are nitrogen, oxygen, sulfur and phosphorus.

It will be noted that the structure of some of the compounds of this invention includes asymmetric carbon atoms. It is to be understood accordingly that the isomers arising from such asymmetry are included within the scope of this invention. Such isomers are obtained in substantially pure form by classical separation techniques and by sterically controlled synthesis.

The term "can be removed *in vivo*", as used herein, refers to a group that can be cleaved *in vivo*, either enzymatically or non-enzymatically. For example, amides can be cleaved by amidases, and N-methyl amines can be cleaved by enzymatic oxidation. For example, when deprenyl is administered to a subject, it is believed, as described *infra*, that the methyl group can be removed *in vivo* to yield an active compound. As a further example, with reference to Formula I, when R_1 is alkylcarbonyl, the resulting amide group can be hydrolytically cleaved *in vivo*, enzymatically or non-enzymatically, to yield a deprenyl compound including a secondary amine (e.g., R_1 is converted to hydrogen *in vivo*). Other groups which can be removed *in vivo* are known (see, e.g., R.B. Silverman (1992) "The Organic Chemistry of Drug

Design and Drug Action", Academic Press, San Diego) and can be employed in compounds useful in the present invention.

II. Pharmaceutical Compositions

The phrase "pharmaceutically acceptable" is employed herein to refer to those 5 compounds, materials, compositions, and/or dosage forms which are, within the scope of sound medical judgment, suitable for use in contact with the tissues of human beings and animals without excessive toxicity, irritation, allergic response, or other problem or complication, commensurate with a reasonable benefit/risk ratio.

The phrase "pharmaceutically-acceptable carrier" as used herein means a 10 pharmaceutically-acceptable material, composition or vehicle, such as a liquid or solid filler, diluent, excipient, solvent or encapsulating material, involved in carrying or transporting the subject deprenyl compound from one organ, or portion of the body, to another organ, or portion of the body. Each carrier must be "acceptable" in the sense of being compatible with the other ingredients of the formulation and not injurious to the patient. Some examples of materials 15 which can serve as pharmaceutically-acceptable carriers include: (1) sugars, such as lactose, glucose and sucrose; (2) starches, such as corn starch and potato starch; (3) cellulose, and its derivatives, such as sodium carboxymethyl cellulose, ethyl cellulose and cellulose acetate; (4) powdered tragacanth; (5) malt; (6) gelatin; (7) talc; (8) excipients, such as cocoa butter and suppository waxes; (9) oils, such as peanut oil, cottonseed oil, safflower oil, sesame oil, olive 20 oil, corn oil and soybean oil; (10) glycols, such as propylene glycol; (11) polyols, such as glycerin, sorbitol, mannitol and polyethylene glycol; (12) esters, such as ethyl oleate and ethyl laurate; (13) agar; (14) buffering agents, such as magnesium hydroxide and aluminum hydroxide; (15) alginic acid; (16) pyrogen-free water; (17) isotonic saline; (18) Ringer's solution; (19) ethyl alcohol; (20) phosphate buffer solutions; and (21) other non-toxic 25 compatible substances employed in pharmaceutical formulations.

The stability of deprenyl can be affected by the pH of the medium in which the deprenyl is formulated. For example, deprenyl is more stable at a pH in the range of about 3-5 than at a pH of about 7. Therefore, when formulating a deprenyl compound in a pharmaceutical composition, it is preferred that the deprenyl compound be maintained at a suitable pH. In 30 preferred embodiments, a pharmaceutical composition of the invention has a pH in the range of about 3 to about 5, more preferably about 3 to about 4. Furthermore, ethyl alcohol is a preferred solvent for improving stability of deprenyl. Thus, in certain embodiments, alcoholic or aqueous alcoholic media are preferred for the pharmaceutical compositions of the invention.

As set out above, certain embodiments of the present deprenyl compounds may contain 35 a basic functional group, such as amino or alkylamino, and are, thus, capable of forming pharmaceutically-acceptable salts with pharmaceutically-acceptable acids. The term

"pharmaceutically-acceptable salts" in this respect, refers to the relatively non-toxic, inorganic and organic acid addition salts of compounds of the present invention. These salts can be prepared *in situ* during the final isolation and purification of the compounds of the invention, or by separately reacting a purified compound of the invention in its free base form with a suitable 5 organic or inorganic acid, and isolating the salt thus formed. Representative salts include the hydrobromide, hydrochloride, sulfate, bisulfate, phosphate, nitrate, acetate, valerate, oleate, palmitate, stearate, laurate, benzoate, lactate, phosphate, tosylate, citrate, maleate, fumarate, succinate, tartrate, naphthylate, mesylate, glucoheptonate, lactobionate, and laurylsulfonate salts and the like (see, for example, Berge et al. (1977) "Pharmaceutical Salts", *J. Pharm. Sci.* 10 66:1-19).

In other cases, the deprenyl compounds of the present invention may contain one or more acidic functional groups and, thus, are capable of forming pharmaceutically-acceptable salts with pharmaceutically-acceptable bases. The term "pharmaceutically-acceptable salts" in these instances refers to the relatively non-toxic, inorganic and organic base addition salts of 15 compounds of the present invention. These salts can likewise be prepared *in situ* during the final isolation and purification of the compounds, or by separately reacting the purified compound in its free acid form with a suitable base, such as the hydroxide, carbonate or bicarbonate of a pharmaceutically-acceptable metal cation, with ammonia, or with a pharmaceutically-acceptable organic primary, secondary or tertiary amine. Representative alkali 20 or alkaline earth salts include the lithium, sodium, potassium, calcium, magnesium, and aluminum salts and the like. Representative organic amines useful for the formation of base addition salts include ethylamine, diethylamine, ethylenediamine, ethanolamine, diethanolamine, piperazine and the like (see, for example, Berge et al., *supra*).

Wetting agents, emulsifiers and lubricants, such as sodium lauryl sulfate and 25 magnesium stearate, as well as coloring agents, release agents, coating agents, sweetening, flavoring and perfuming agents, preservatives and antioxidants can also be present in the compositions.

Examples of pharmaceutically-acceptable antioxidants include: (1) water soluble 30 antioxidants, such as ascorbic acid, cysteine hydrochloride, sodium bisulfate, sodium metabisulfite, sodium sulfite and the like; (2) oil-soluble antioxidants, such as ascorbyl palmitate, butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), lecithin, propyl gallate, alpha-tocopherol, and the like; and (3) metal chelating agents, such as citric acid, ethylenediamine tetraacetic acid (EDTA), sorbitol, tartaric acid, phosphoric acid, and the like.

Formulations of the present invention include those suitable for oral, nasal, topical 35 (including buccal and sublingual), rectal, vaginal and/or parenteral administration. The formulations may conveniently be presented in unit dosage form and may be prepared by any

methods well known in the art of pharmacy. The amount of active ingredient which can be combined with a carrier material to produce a single dosage form will vary depending upon the host being treated, the particular mode of administration. The amount of active ingredient which can be combined with a carrier material to produce a single dosage form will generally be that amount of the deprenyl compound which produces a therapeutic effect. Generally, out of one hundred per cent, this amount will range from about 0.01 per cent to about ninety-nine percent of active ingredient, preferably from about 0.1 per cent to about 70 per cent, most preferably from about 1 per cent to about 30 per cent.

Methods of preparing these formulations or compositions include the step of bringing into association at least one deprenyl compound of the present invention with the carrier and, optionally, one or more accessory ingredients. In general, the formulations are prepared by uniformly and intimately bringing into association a deprenyl compound of the present invention with liquid carriers, or finely divided solid carriers, or both, and then, if necessary, shaping the product.

Formulations of the invention suitable for oral administration may be in the form of capsules, cachets, pills, tablets, lozenges (using a flavored basis, usually sucrose and acacia or tragacanth), powders, granules, or as a solution or a suspension in an aqueous or non-aqueous liquid, or as an oil-in-water or water-in-oil liquid emulsion, or as an elixir or syrup, or as pastilles (using an inert base, such as gelatin and glycerin, or sucrose and acacia) and/or as mouth washes and the like, each containing a predetermined amount of a compound of the present invention as an active ingredient. A deprenyl compound of the present invention may also be administered as a bolus, electuary or paste.

In solid dosage forms of the invention for oral administration (capsules, tablets, pills, dragees, powders, granules and the like), the active ingredient is mixed with one or more pharmaceutically-acceptable carriers, such as sodium citrate or dicalcium phosphate, and/or any of the following: (1) fillers or extenders, such as starches, lactose, sucrose, glucose, mannitol, and/or silicic acid; (2) binders, such as, for example, carboxymethylcellulose, alginates, gelatin, polyvinyl pyrrolidone, sucrose and/or acacia; (3) humectants, such as glycerol; (4) disintegrating agents, such as agar-agar, calcium carbonate, potato or tapioca starch, alginic acid, certain silicates, and sodium carbonate; (5) solution retarding agents, such as paraffin; (6) absorption accelerators, such as quaternary ammonium compounds; (7) wetting agents, such as, for example, cetyl alcohol and glycerol monostearate; (8) absorbents, such as kaolin and bentonite clay; (9) lubricants, such a talc, calcium stearate, magnesium stearate, solid polyethylene glycols, sodium lauryl sulfate, and mixtures thereof; and (10) coloring agents. In the case of capsules, tablets and pills, the pharmaceutical compositions may also comprise buffering agents. Solid compositions of a similar type may also be employed as fillers in soft

and hard-filled gelatin capsules using such excipients as lactose or milk sugars, as well as high molecular weight polyethylene glycols and the like.

A tablet may be made by compression or molding, optionally with one or more accessory ingredients. Compressed tablets may be prepared using binder (for example, gelatin or hydroxypropylmethyl cellulose), lubricant, inert diluent, preservative, disintegrant (for example, sodium starch glycolate or cross-linked sodium carboxymethyl cellulose), surface-active or dispersing agent. Molded tablets may be made by molding in a suitable machine a mixture of the powdered deprenyl compound moistened with an inert liquid diluent.

The tablets, and other solid dosage forms of the pharmaceutical compositions of the present invention, such as dragees, capsules, pills and granules, may optionally be scored or prepared with coatings and shells, such as enteric coatings and other coatings well known in the pharmaceutical-formulating art. They may also be formulated so as to provide slow or controlled release of the active ingredient therein using, for example, hydroxypropylmethyl cellulose in varying proportions to provide the desired release profile, other polymer matrices, liposomes and/or microspheres. They may be sterilized by, for example, filtration through a bacteria-retaining filter, or by incorporating sterilizing agents in the form of sterile solid compositions which can be dissolved in sterile water, or some other sterile injectable medium immediately before use. These compositions may also optionally contain opacifying agents and may be of a composition that they release the active ingredient(s) only, or preferentially, in a certain portion of the gastrointestinal tract, optionally, in a delayed manner. Examples of embedding compositions which can be used include polymeric substances and waxes. The active ingredient can also be in micro-encapsulated form, if appropriate, with one or more of the above-described excipients.

Liquid dosage forms for oral administration of the deprenyl compounds of the invention include pharmaceutically acceptable emulsions, microemulsions, solutions, suspensions, syrups and elixirs. In addition to the active ingredient, the liquid dosage forms may contain inert diluents commonly used in the art, such as, for example, water or other solvents, solubilizing agents and emulsifiers, such as ethyl alcohol, isopropyl alcohol, ethyl carbonate, ethyl acetate, benzyl alcohol, benzyl benzoate, propylene glycol, 1,3-butylene glycol, oils (in particular, cottonseed, groundnut, corn, germ, olive, castor and sesame oils), glycerol, tetrahydrofuryl alcohol, polyethylene glycols and fatty acid esters of sorbitan, and mixtures thereof.

Besides inert diluents, the oral compositions can also include adjuvants such as wetting agents, emulsifying and suspending agents, sweetening, flavoring, coloring, perfuming and preservative agents.

Suspensions, in addition to the active deprenyl compound, may contain suspending agents as, for example, ethoxylated isostearyl alcohols, polyoxyethylene sorbitol and sorbitan

esters, microcrystalline cellulose, aluminum metahydroxide, bentonite, agar-agar and tragacanth, and mixtures thereof.

Formulations of the pharmaceutical compositions of the invention for rectal or vaginal administration may be presented as a suppository, which may be prepared by mixing one or more deprenyl compounds of the invention with one or more suitable nonirritating excipients or carriers comprising, for example, cocoa butter, polyethylene glycol, a suppository wax or a salicylate, and which is solid at room temperature, but liquid at body temperature and, therefore, will melt in the rectum or vaginal cavity and release the deprenyl compound.

Formulations of the present invention which are suitable for vaginal administration also include pessaries, tampons, creams, gels, pastes, foams or spray formulations containing such carriers as are known in the art to be appropriate.

Dosage forms for the topical or transdermal administration of a deprenyl compound of this invention include powders, sprays, ointments, pastes, creams, lotions, gels, solutions, patches and inhalants. The active compound may be mixed under sterile conditions with a pharmaceutically-acceptable carrier, and with any preservatives, buffers, or propellants which may be required.

The ointments, pastes, creams and gels may contain, in addition to a deprenyl compound of this invention, these substances. Sprays can additionally contain excipients, such as animal and vegetable fats, oils, waxes, paraffins, starch, tragacanth, cellulose derivatives, polyethylene glycols, silicones, bentonites, silicic acid, talc and zinc oxide, or mixtures thereof.

Powders and sprays can contain, in addition to a compound of this invention, excipients such as lactose, talc, silicic acid, aluminum hydroxide, calcium silicates and polyamide powder, or mixtures of customary propellants, such as chlorofluorohydrocarbons and volatile unsubstituted hydrocarbons, such as butane and propane.

Transdermal patches have the added advantage of providing controlled delivery of a compound of the present invention to the body. Such dosage forms can be made by dissolving or dispersing the deprenyl compound in the proper medium. Absorption enhancers can also be used to increase the flux of the deprenyl compound across the skin. The rate of such flux can be controlled by either providing a rate controlling membrane or dispersing the deprenyl compound in a polymer matrix or gel. Devices, including patches, which transdermally deliver a deprenyl compound by iontophoresis or other electrically-assisted methods can also be employed in the present invention, including, for example, the devices described in U.S. Patent Nos. 4,708,716 and 5,372,579.

Ophthalmic formulations, eye ointments, powders, solutions, drops, sprays and the like, are also contemplated as being within the scope of this invention.

Pharmaceutical compositions of this invention suitable for parenteral administration comprise one or more deprenyl compounds of the invention in combination with one or more pharmaceutically-acceptable sterile isotonic aqueous or nonaqueous solutions, dispersions, suspensions or emulsions, or sterile powders which may be reconstituted into sterile injectable solutions or dispersions just prior to use, which may contain antioxidants, buffers, bacteriostats, solutes which render the formulation isotonic with the blood of the intended recipient or suspending or thickening agents.

Examples of suitable aqueous and nonaqueous carriers which may be employed in the pharmaceutical compositions of the invention include water, ethanol, polyols (such as glycerol, propylene glycol, polyethylene glycol, and the like), and suitable mixtures thereof, vegetable oils, such as olive oil, and injectable organic esters, such as ethyl oleate. Proper fluidity can be maintained, for example, by the use of coating materials, such as lecithin, by the maintenance of the required particle size in the case of dispersions, and by the use of surfactants.

These compositions may also contain adjuvants such as preservatives, wetting agents, emulsifying agents and dispersing agents. Prevention of the action of microorganisms may be ensured by the inclusion of various antibacterial and antifungal agents, for example, paraben, chlorobutanol, phenol sorbic acid, and the like. It may also be desirable to include isotonic agents, such as sugars, sodium chloride, and the like into the compositions. In addition, prolonged absorption of the injectable pharmaceutical form may be brought about by the inclusion of agents which delay absorption such as aluminum monostearate and gelatin.

In some cases, in order to prolong the effect of a drug, it is desirable to slow the absorption of the drug from subcutaneous or intramuscular injection. This may be accomplished by the use of a liquid suspension of crystalline or amorphous material having poor water solubility. The rate of absorption of the drug then depends upon its rate of dissolution which, in turn, may depend upon crystal size and crystalline form. Alternatively, delayed absorption of a parenterally-administered drug form is accomplished by dissolving or suspending the drug in an oil vehicle.

Injectable depot forms are made by forming microencapsulated matrices of the subject deprenyl compounds in biodegradable polymers such as polylactide-polyglycolide. Depending on the ratio of drug to polymer, and the nature of the particular polymer employed, the rate of drug release can be controlled. Examples of other biodegradable polymers include poly(orthoesters) and poly(anhydrides). Depot injectable formulations are also prepared by entrapping the drug in liposomes or microemulsions which are compatible with body tissue.

When the compounds of the present invention are administered as pharmaceuticals, to humans and animals, they can be given alone or as a pharmaceutical composition containing,

for example, 0.01 to 99.5% (more preferably, 0.1 to 90%) of active ingredient in combination with a pharmaceutically acceptable carrier.

The preparations of the present invention may be given orally, parenterally, topically, or rectally. They are of course given by forms suitable for each administration route. For example, they are administered in tablets or capsule form, by injection, inhalation, eye lotion, ointment, suppository, etc.; administration by injection, infusion or inhalation; topical by lotion or ointment; and rectal by suppositories. Injection (subcutaneous or intraperitoneal) or topical ophthalmic administration are preferred.

The phrases "parenteral administration" and "administered parenterally" as used herein means modes of administration other than enteral and topical administration, usually by injection, and includes, without limitation, intravenous, intramuscular, intraarterial, intrathecal, intracapsular, intraorbital, intracardiac, intradermal, intraperitoneal, transtracheal, subcutaneous, subcuticular, intraarticular, subcapsular, subarachnoid, intraspinal and intrasternal injection and infusion.

The phrases "systemic administration," "administered systemically," "peripheral administration" and "administered peripherally" as used herein mean the administration of a compound, drug or other material other than directly into the central nervous system, such that it enters the patient's system and, thus, is subject to metabolism and other like processes, for example, subcutaneous administration.

These compounds may be administered to humans and other animals for therapy by any suitable route of administration, including orally, nasally, as by, for example, a spray, rectally, intravaginally, parenterally, intracisternally and topically, as by powders, ointments or drops, including buccally and sublingually.

Regardless of the route of administration selected, the compounds of the present invention, which may be used in a suitable hydrated form, and/or the pharmaceutical compositions of the present invention, are formulated into pharmaceutically-acceptable dosage forms by conventional methods known to those of skill in the art.

Actual dosage levels of the active ingredients in the pharmaceutical compositions of this invention may be varied so as to obtain an amount of the active ingredient which is effective to achieve the desired therapeutic response for a particular patient, composition, and mode of administration, without being toxic to the patient.

The selected dosage level will depend upon a variety of factors including the activity of the particular deprenyl compound of the present invention employed, or the ester, salt or amide thereof, the route of administration, the time of administration, the rate of excretion of the particular compound being employed, the duration of the treatment, other drugs, compounds

and/or materials used in combination with the particular deprenyl compound employed, the age, sex, weight, condition, general health and prior medical history of the patient being treated, and like factors well known in the medical arts.

A physician or veterinarian having ordinary skill in the art can readily determine and
5 prescribe the effective amount of the pharmaceutical composition required. For example, the physician or veterinarian could start doses of the compounds of the invention employed in the pharmaceutical composition at levels lower than that required in order to achieve the desired therapeutic effect and gradually increase the dosage until the desired effect is achieved.

In general, a suitable daily dose of a deprenyl compound of the invention will be that
10 amount of the compound which is the lowest dose effective to produce a therapeutic effect. Such an effective dose will generally depend upon the factors described above. Generally, intraperitoneal and subcutaneous doses of the compounds of this invention for a patient, when used for the indicated nerve-cell rescuing effects, will range from about 0.0001 to about 10 mg per kilogram of body weight per day, more preferably from about 0.001 mg/kg to about 1
15 mg/kg per day.

If desired, the effective daily dose of a deprenyl compound may be administered as two, three, four, five, six or more sub-doses administered separately at appropriate intervals throughout the day, optionally, in unit dosage forms.

While it is possible for a compound of the present invention to be administered alone, it
20 is preferable to administer the compound as a pharmaceutical formulation (composition). It will be understood that two or more deprenyl compounds can be administered in a single therapeutic composition.

Therapeutic compositions can be administered with medical devices known in the art. For example, in a preferred embodiment, a therapeutic composition of the invention can be
25 administered with a needleless hypodermic injection device, such as the devices disclosed in U.S. Patent Nos. 5,399,163, 5,383,851, 5,312,335, 5,064,413, 4,941,880, 4,790,824, or 4,596,556. Examples of well-known implants and modules useful in the present invention include: U.S. Patent No. 4,487,603, which discloses an implantable micro-infusion pump for dispensing medication at a controlled rate; U.S. Patent No. 4,486,194, which discloses a
30 therapeutic device for administering medicants through the skin; U.S. Patent No. 4,447,233, which discloses a medication infusion pump for delivering medication at a precise infusion rate; U.S. Patent No. 4,447,224, which discloses a variable flow implantable infusion apparatus for continuous drug delivery; U.S. Patent No. 4,439,196, which discloses an osmotic drug delivery system having multi-chamber compartments; and U.S. Patent No. 4,475,196, which
35 discloses an osmotic drug delivery system. These patents are incorporated herein by reference.

Many other such implants, delivery systems, and modules are well known to those skilled in the art.

It is believed that certain deprenyl compounds can be at least partially metabolized *in vivo* after administration to a subject. For example, (-)-deprenyl can be metabolized by the liver to (-)-desmethyldeprenyl, as well as (-)-methamphetamine and (-)-amphetamine, after oral administration. The hepatic metabolism of (-)-deprenyl can be inhibited by administration of a P450 inhibitor such as Proadifen. In animal and cell-culture studies, administration of Proadifen reduces the ability of (-)-deprenyl to prevent cell death, but does not block the cell-rescuing activity of (-)-desmethyldeprenyl. Thus, it is believed that at least one metabolite of (-)-deprenyl, most likely (-)-desmethyldeprenyl, is an active compound. It is presently believed that (-)-methamphetamine and (-)-amphetamine are inhibitors of the cell-rescuing activity of deprenyl compounds. It is also believed that monoamine oxidase (MAO, including both MAO-A and MAO-B) inhibitory activity is not required for nerve-cell rescuing activity. Absence of MAO inhibitor activity may in fact provide a drug with fewer side effects. Thus, in certain embodiments, it is preferred that the deprenyl compound have low MAO inhibitor activity, or be administered so as to minimize MAO inhibition (e.g., by use of a suitable prodrug or formulation).

In view of the foregoing, it is preferable to administer deprenyl compounds by a route that minimizes metabolism to inhibitor compounds such as (-)-methamphetamine and (-)-amphetamine, while allowing metabolism to active compounds such as (-)-desmethyldeprenyl. Metabolism to an active compound can occur at the desired site of activity, e.g., in the target organ or area, e.g., the brain. Thus, prodrugs, which are metabolized to active compounds, are useful in the methods of the invention.

It has been found that certain deprenyl compounds have greater therapeutic efficacy (e.g., are effective at lower doses) when administered so as to decrease or prevent the "first-pass" effect. Accordingly, intraperitoneal or especially subcutaneous injection are preferred routes of administration. In preferred embodiments, a deprenyl compound is administered in divided doses. For example, a deprenyl compound can be administered by frequent (e.g., pulsed) injections, or by a controlled infusion, which can be constant or programmably varied as described above. In preferred embodiments in which a deprenyl compound is administered orally, the deprenyl compound can be formulated to reduce the amount of hepatic metabolism after oral administration and thereby improve the therapeutic efficacy.

In certain embodiments, the deprenyl compounds of the invention can be formulated to ensure proper distribution *in vivo*. For example, the blood-brain barrier (BBB) excludes many highly hydrophilic compounds. To ensure that the therapeutic compounds of the invention cross the BBB (if desired), they can be formulated, for example, in liposomes. For methods of

manufacturing liposomes, see, e.g., U.S. Patents 4,522,811; 5,374,548; and 5,399,331. The liposomes may comprise one or more moieties which are selectively transported into specific cells or organs ("targeting moieties"), thus providing targeted drug delivery (see, e.g., V.V. Ranade (1989) *J. Clin. Pharmacol.* 29:685). Exemplary targeting moieties include folate or
5 biotin (see, e.g., U.S. Patent 5,416,016 to Low *et al.*); mannosides (Umezawa *et al.*, (1988) *Biochem. Biophys. Res. Commun.* 153:1038); antibodies (P.G. Bloeman *et al.* (1995) *FEBS Lett.* 357:140; M. Owais *et al.* (1995) *Antimicrob. Agents Chemother.* 39:180); surfactant protein A receptor (Briscoe *et al.* (1995) *Am. J. Physiol.* 1233:134); gp120 (Schreier *et al.* (1994) *J. Biol. Chem.* 269:9090); see also K. Keinanen; M.L. Laukkanen (1994) *FEBS Lett.* 346:123; J.J. Killion; I.J. Fidler (1994) *Immunomethods* 4:273. In a preferred embodiment, the therapeutic compounds of the invention are formulated in liposomes; in a more preferred embodiment, the liposomes include a targeting moiety.
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The invention is further illustrated by the following study, which should in no way be construed as being further limiting. The contents of all references, pending patent applications and published patent applications, cited throughout this application are hereby incorporated by reference. It should be understood that the animal models for nerve cell rescue used in the study are accepted and that a demonstration of efficacy in these models is predictive of efficacy in humans.
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1.0 Introduction

1.1 Overview

Glial and neuronal numbers in the mammalian central nervous system (CNS) are determined as a result of the progression of cells through a series of temporal stages including induction, proliferation, migration, differentiation, degeneration and death. Cell degeneration and death are critical processes, which ultimately serve to counterbalance proliferation and decide the total numbers of cells in any specific region of the CNS. It is thought that cell degeneration and death mechanisms occur in order to eliminate functionally inappropriate, damaged or abnormal cells that could impair or interfere with the operation of a particular neural structure. For more than forty years, cell death has been recognized to be central to nervous system development (Glucksmann, 1951; Saunders, 1966). During development, cells are generated in excess and functionally inappropriate cells degenerate and are eliminated during so called critical developmental periods.

Inadequate survival signals have been suggested to be one of the predominant initiating events for the mechanisms of developmental cell death in the CNS (Raff, 1992). The exchange of trophic signals between cells is now known to be a major factor in the determination of which cells survive and which cells degenerate and die during development. An understanding of trophic signaling in nervous system development now appears to be relevant to the pathogenesis of some glial and neuronal degenerative diseases (Tatton *et al.*, 1997).

Cell death is now recognized to proceed by three different processes, apoptosis, necrosis and atrophy (Ellis *et al.*, 1991). The study of Kerr *et al.* (1972) was one of the

first to differentiate apoptosis from necrosis on the basis of differences in cytology. Cell swelling and breakdown of the external membranes of the cell were known to be typical features of necrosis. Using electron microscopy, Kerr and his colleagues described nuclear degradation, particularly chromatin condensation, in cells that retained intact cell membranes. Because the cells underwent shrinkage rather than swelling, they termed the process 'shrinkage necrosis'. Shrinkage necrosis was subsequently termed apoptosis. Subsequently, Kerr's colleague, Wyllie and his associates, recognized that endonuclease-mediated nuclear DNA cleavage is a principal identifying feature of nuclear degradation in apoptosis (Arends *et al.*, 1990). The third cell death process, atrophy, involves the gradual shrinkage and progressive dysfunction of cells that has been found to accompany nervous system aging (Finch, 1993). Apoptosis can occur over hours or days while necrosis occurs within minutes to hours of insult presentation. Atrophy on the other hand is protracted and occurs over months or years.

Naturally occurring apoptosis is difficult to study since apoptotic nuclei are short-lived and the cells enter apoptosis in highly desynchronized manner. Only a small proportion of cells are in the apoptotic process at any time point so that biochemical or molecular methods are faced with the difficulty of detecting changes that accrue from only a few apoptotic cells mixed with large numbers of normal cells. Accordingly, models in which cells enter apoptosis in a highly synchronized manner have been extremely valuable in studying the mechanisms underlying the apoptotic process. Models in which trophic support is suddenly withdrawn from cultured cells have proven to be particularly valuable. Furthermore, the study of apoptotic mechanisms has largely been facilitated by the development of light microscopic techniques that detect nuclear DNA

cleavage and/or chromatin condensation *in situ* (see (Tatton *et al.*, 1997)). The *in situ* methods allow the relatively small proportion of apoptotic cells to be directly examined while using their unaffected neighbors as controls (see (Wadia *et al.*, 1998)).

Most studies of nervous system apoptosis have focused on nerve cells. Relatively little attention has been paid to glial cell apoptosis. Glia, derived from the Greek word for glue, were initially thought of as cells which simply provide a framework to hold neuronal cells together. It is now known that glia subserve a number of roles in nervous system operation and that those roles are considerably more critical than just holding the neurons together (Travis, 1994).

One of those roles involves the facilitation of action potential transmission by the myelination of nerve cell axons. In the mammalian central nervous system, myelination is carried out by oligodendrocytes that synthesize myelin, a lipid rich biological membrane, which forms into multilamellar sheaths. Astrocytes are involved in a number of functions, most notably as guides for neuronal migration, process outgrowth and the synthesis and provision of a number of neurotrophic factors. Microglia, the third glial cell type, are bone marrow derived macrophages which function as immunocompetent cells in the CNS.

1.2 Oligodendrocyte Differentiation

Oligodendrocytes are generated postnatally from undifferentiated pluripotential cells. Two major alternate cell types are generated from these pluripotent cells: oligodendrocytes and type-2 astrocytes. Cells expressing the antigenic phenotype of oligodendrocytes are first detected around the time of birth in rats while the first

appearance of type-2 astrocytes occurs at 7-10 days after birth (Abney *et al.*, 1981; Miller *et al.*, 1985). In the rat CNS, three main oligodendroglial cell lineage have been identified. They are the undifferentiated oligodendrocyte - type 2 astrocyte (O-2A) progenitor cells, the partially differentiated proligodendrocytes (PROLs) and the fully differentiated oligodendrocytes (OLs).

Most of the information on oligodendrocyte ontogeny has been obtained from *in vitro* studies using dissociated cultures from neonatal rat or mouse cortex or rat optic nerve (Gard and Pfeiffer, 1989; Norton and Farooq, 1993). Primary cultures of oligodendroglial cells provide a powerful model system to study the regulation of differentiation, function and death. Cultured oligodendrocytes mimic their *in vivo* counterparts in that they synthesize myelin specific proteins and also produce myelin-like membranes (Knapp *et al.*, 1987; Szuchet *et al.*, 1986). Oligodendrocytes *in vitro* can be maintained in chemically-defined media containing low serum which allows for the study of the actions of specific molecules on the cells.

1.2.1 Oligodendrocyte-type 2 astrocyte (O-2A) progenitors

The characterization of the O-2A lineage cells in the last decade has facilitated an understanding of glial cell development. Several studies have shown that O-2A progenitor cells are bipotential and can undergo differentiation along two lines into either oligodendrocytes or type-2 astrocytes. The O-2A cells display a high degree of developmental plasticity and their differentiation can be manipulated by placement into a defined *in vitro* environment (Saneto and de Vellis, 1985). Extracellular signaling molecules like serum and trophic factors and cell-intrinsic factors regulate the sequential

differentiation of the O-2A progenitor cells. Culture of O-2A progenitors in low serum conditions causes them to differentiate into oligodendrocytes. Higher concentrations (10% or more) of fetal calf serum induce their differentiation into a type-2, process bearing astrocytes (Raff *et al.*, 1983; Temple and Raff, 1985).

Developmental studies have shown that O-2A progenitor cells originate in the subventricular zone of the forebrain, the subependymal layers of the 4th ventricle and in the ventral spinal cord (Curtis *et al.*, 1988; LeVine and Goldman, 1988; Pringle and Richardson, 1993; Reynolds and Wilkin, 1988; Warf *et al.*, 1991). Prior to migrating from those sites, the cells proliferate. In the rat brain, an initial population of O-2A progenitors of about 5×10^5 cells generates about 60×10^6 oligodendrocytes. O-2A progenitor cells are highly motile and migrate from the germinal zones of origin into widespread regions of the developing CNS including the subcortical white matter, cerebellum, spinal cord and the optic nerve (Small *et al.*, 1987; Warf *et al.*, 1991). After migrating to their final destinations, the O-2A cells differentiate into PROLs and OLs capable of initiating myelination.

1.2.2 Maturation of O-2A Progenitors

The bipolar O-2A progenitor cells differentiate into intermediate, multipolar PROLs (Gard and Pfeiffer, 1990). The PROLs further differentiate into complex, multipolar OLs (Gard and Pfeiffer, 1989; Raff, 1989).

Initially, the cells of the O-2A lineage were characterized only on the basis of their morphologies. Later studies showed that different cells in the oligodendrocyte lineage express specific developmental marker proteins (Raff *et al.*, 1979; Reynolds and Wilkin,

1988). The bipolar O-2A progenitor cell can be recognized by antibodies against a three surface tetragangliosides, A2B5, LB1 and GD3 (Levi *et al.*, 1987; Raff *et al.*, 1983; Reynolds and Wilkin, 1988). The O-2A progenitor cells do not express the astrocyte specific intermediate filament protein, glial fibrillary acidic protein (GFAP). PROLs begin to express surface galactosphingolipids like galactocerebroside (GC) (Raff *et al.*, 1979) and cyclic nucleotide phosphorylase-I (CNPase-I) but do not express A2B5, LB1 or GD3 (Mirsky *et al.*, 1980. OLs are immunopositive for GC and CNPase-I but also express reactivity to myelin basic protein (MBP) and proteolipid protein (PLP) (Dubois Dalcq, 1987; Zeller *et al.*, 1985). As well as MBP and PLP, OLs express a number of other myelin related proteins including myelin oligodendrocyte glycoprotein (MOG) and myelin associated glycoprotein (MAG) (Dubois Dalcq *et al.*, 1986). MBP forms 30 to 40% of CNS myelin protein while PLP forms 50% of the protein mass of myelin. MBP and PLP are present in the complex processes of mature OLs.

In order to study apoptosis in the oligodendrocytic and type-2 astrocytic lineage, I developed pure cultures enriched in O-2A progenitor cells using a modified differential shake-off procedure (McCarthy, 1980). The O-2A progenitor cells were differentiated in the presence of insulin and IGF-I. Individual cell types in the lineage were identified by combining immunocytochemistry for antibodies against cell specific marker proteins with morphologic identification criteria. The approach allowed comparisons of apoptotic events and the effects of anti-apoptotic agents in the different cell types.

1.2.3 Trophic Factor Regulation of Oligodendrocyte Differentiation

The differentiation of O-2A progenitor cells into OLs is influenced by a number of polypeptide trophic factors including platelet derived growth factor (PDGF), basic fibroblast growth factor (bFGF), ciliary neurotrophic factor (CNTF), insulin and insulin-like growth factor-I (IGF-I) (Barres and Raff, 1994). *In vivo*, the trophic factors can be synthesized by either neurons or astrocytes or both. CNTF induces the differentiation of O-2A cells into type-2 astrocytes while PDGF induces O-2A cell differentiation into OLs (Lillien and Raff, 1990). In the presence of PDGF, the O-2A progenitor cells generally undergo about 8 divisions before synchronously differentiating into OLs (Noble *et al.*, 1988; Raff *et al.*, 1988; Richardson *et al.*, 1988). Factors like bFGF are mitogenic for the O-2A progenitor cells and keep the O-2A cells in the mitotic cycle thereby preventing their differentiation into OLs. In contrast, insulin and IGF-I have been shown to induce irreversible OL differentiation (McMorris and Dubois Dalcq, 1988; Raff *et al.*, 1983).

1.3 Oligodendroglial Death

1.3.1 Developmental Death of O-2A Lineage Cells

Glial cells, particularly O-2A cells, are over produced during nervous system development. *In vivo* developmental studies have revealed that more than 50% of the newly formed O-2A progenitor cells undergo apoptosis (Barres *et al.*, 1992). The O-2A apoptosis has been seen to occur prior to differentiation and myelination of neuronal axons. The massive O-2A cell death has been hypothesized to occur in order to limit OL numbers at levels that are appropriate to the axon surface areas requiring myelination.

Cell death is not limited to the O-2A progenitor cell populations but also is seen the OLs. Recent studies have indicated that premyelinating OLs that go on to differentiate into myelinating OLs undergo cell death (Trapp *et al.*, 1997). Although the developmental cell death of OLs is now well recognized, it has not been determined whether or not it is apoptotic. If it is apoptotic, it is not known whether the process involves mitochondrial decisional points (see below) or whether it is responsive to anti-apoptotic compounds like (-)-deprenyl.

1.3.2 Oligodendrocyte Death in Pathological Conditions

OL death occurs not only during development but also in some pathological conditions. In human demyelinating diseases, like multiple sclerosis (MS), neurological manifestations depend on the axon populations that are involved by the demyelinating lesions and the functional deficits that result from impaired conduction in those axons. Neuropathological examination of the demyelinating MS foci has revealed a pronounced decrease in OL numbers, suggesting that the process involves OL death (Bruck *et al.*, 1994). Loss of OLs has been observed in both acute and chronic MS lesions.

The pathogenesis of MS has not been fully explained. The disease has been thought to result from a number of causes principally aberrant autoimmunity directed against myelin antigens, possibly triggered by ubiquitous ribonucleic acid or deoxyribonucleic acid viruses (Scolding *et al.*, 1994; Simon and Neubert, 1996; Tienari, 1994). An inflammatory response accompanies the breakdown of myelin and the response is thought to be initiated by perivascular infiltration of CD4⁺ T lymphocytes (Raine, 1994). It is believed that the activated T lymphocytes produce cytokines like

lymphotoxin and tumor necrosis factor (TNF) which consequently act as major mediators of OL injury (Selmaj *et al.*, 1991; Selmaj and Raine, 1988). According to the view that an immune attack causes myelin damage and the consequences of the myelin damage result in OL damage, the decreased OL numbers in MS foci would be the result of OL death secondary to demyelination. Alternately though, immune or other damage to OLs could cause OL apoptosis with a resulting demyelination so that the decrease in OL numbers would be the primary rather than the secondary event in MS.

The decreased numbers of OLs in MS foci could also result from damage to the oligodendrocyte progenitor cells. Damage to O-2A progenitor cells could result from demyelinating periventricular lesions which are found in about 90% of MS brains (Lumsden, 1971). Periventricular lesions result in damage to the O-2A progenitor cells concentrated in the subependymal layer. The damaged oligodendrocyte progenitor cells would be unavailable to migrate from the subependymal layer and to replace OLs lost in the MS foci.

1.3.3 Oligodendrocytes and OL Progenitors Require Trophic Factors For Survival

Trophic factors have been considered above relative to their roles in influencing OL and type-2 astrocyte lineage differentiation. They also may play an important role in determining the survival of cells in the two lineages. There has been great interest in the role of trophic factors in the prevention of the death of neuronal cells (Thoenen, 1991). For example, trophic factors like CNTF, have been shown to ameliorate cell death of motoneurons *in vivo* when applied directly to the cells (Sendtner *et al.*, 1992) or into the cerebrospinal fluid (Zhang *et al.*, 1995). Other trophic factors, like nerve growth factor

(NGF) prevents the death of several neuronal types like the sympathetic neurons and basal forebrain cholinergic neurons (Hefti, 1986; Oppenheim *et al.*, 1982).

Insulin, IGF-I, CNTF, PDGF and neurotrophins have been shown to increase the survival of OLs (Barres *et al.*, 1992; Barres *et al.*, 1992; Liu *et al.*, 1993; Louis *et al.*, 1993). The factors have also been shown to protect OLs from injury mediated by cytokines like TNF (D'Souza *et al.*, 1996). Studies in the rat optic nerve have suggested that axonal activity modulates the release of the trophic factors (Barres *et al.*, 1993). Both *in vivo* and *in vitro*, astrocytes and neurons are considered to be the chief source of the growth and survival factors (see (Henderson *et al.*, 1994; Seniuk-Tatton *et al.*, 1995) for evidence that both neurons and astrocytes synthesize CNTF).

1.3.4 Effects of Insulin, IGF-I and PDGF on Oligodendrocyte Survival

The importance of IGF-I in the survival of differentiated oligodendrocytes was suggested by the observation of hypermyelination in transgenic mice overexpressing IGF-I (Carson *et al.*, 1993). Other studies reported decreased numbers of oligodendrocytes in mice carrying homozygous disruptions of the IGF-I receptor (Liu *et al.*, 1993). Evidence for IGF-I regulation of normal myelination has also been obtained from nutritional studies (Wiggins, 1982). Those studies observed that nutritional deficiency during the postnatal developmental period in rats or mice resulted in decreased IGF-I levels and that the lowered IGF-I levels were associated with severe hypomyelination.

Studies using neuronal cell lines or primary cultures of neurons or OLs have indicated that not only IGFs' but also insulin regulates cell survival. Several *in vitro* studies have shown that high concentrations of about 10 μ g / ml of insulin is essential for

the survival of neuronal cells in serum free medium (Bottenstein, 1986; Eccleston and Silberberg, 1984; Saneto and de Vellis, 1985). The observation that physiological concentrations of insulin enhanced the numbers of OLs *in vitro* suggested that insulin acted as an analogue of IGF-I by acting through the IGF-I receptors (McMorris, 1983; McMorris *et al.*, 1990).

Insulin and IGF-I appear to act cooperatively to regulate cell survival and death. Not much is known with respect to the role of insulin and IGF-I in regulating oligodendroglial survival, particularly whether their withdrawal leads to OL apoptosis. The present study established a culture model in order to investigate the capacity of insulin and IGF-I withdrawal to initiate OL and type-2 astrocyte lineage apoptosis.

Other studies have utilized *in vitro* systems to examine the effects of trophic factors on the survival of oligodendroglial cells. Using immunopanning techniques *in vitro*, (Barres *et al.*, 1992) examined the survival of O-2A progenitor cells. Their study found that in the absence of serum or growth factors, the O-2A progenitor cells underwent rapid death according to a process, which included features suggestive of apoptosis. PDGF appeared to increase the O-2A progenitor cell survival. Barres and her colleagues performed experiments on O-2A progenitor cell survival in the intact mouse optic nerve. On transplantation of Cos-7 cells engineered to secrete PDGF in the subarachnoid space of the mouse brain, it was observed that in the intact mouse optic nerve, PDGF decreased O-2A cell death by about 85%. Furthermore, the numbers of surviving O-2A progenitor cells in the mouse optic nerve were seen to double over a period of four days.

Several studies have reported that the survival enhancing action of PDGF is

specific to O-2A cells and not to OL cell populations (Hart *et al.*, 1989; McKinnon *et al.*, 1990). It is believed that lack of expression of PDGF receptors on differentiated oligodendroglial cells prevents PDGF from enhancing their survival. Therefore, these studies suggest that the survival of OLs is dependent on the presence of trophic factors other than PDGF, like insulin and IGF-I, yet prior to the experiments described in this thesis, there were no studies of the prevention of OL apoptosis by insulin and IGF-I.

1.4 Apoptotic Cell Death

Our understanding of apoptosis has advanced rapidly over the last several years. Nervous system apoptosis was thought to only result from trophic insufficiency. It is now known that apoptosis can be initiated in neural cells by many different forms of damage and proceeds in a step by step fashion with each step involving signaling by specific proteins. The signaling involves the cleavage, binding, phosphorylation or inter-organelle movements of proteins. The signaling pathways in the early phases of apoptosis depend on the form of damage that initiates the process. Accordingly, specific early pathways can be identified by changes in the levels and/or subcellular locations of specific proteins. The early signaling pathways converge onto a small number of effector signaling pathways that lead to the final degradative steps typical of apoptosis (see (Susin *et al.*, 1996)).

In comparison to necrosis, apoptosis is a private kind of process. In necrosis, cells swell and their plasma membrane fracture allowing their intracellular contents to induce an inflammatory reaction. Inflammatory cytokines and other factors then damage and kill other nearby cells that were not involved in the primary process with the result that

by the formation of membrane wrapped fragments that do not induce an inflammatory reaction. The expression of surface markers on the wrapped fragments causes them to be engulfed by macrophages without damage to nearby cells. Accordingly, individual cells can die by apoptosis without any involvement of their neighbors.

The individuality of apoptosis allows for the process to select specific cells for development without altering the overall organization of a neural structure (see (Raff, 1992)). It also allows apoptosis to serve as a selective defense system that can remove cells which are tumorigenic or infected by viruses (Vaux *et al.*, 1994) without compromising the function of a nervous system structure.

Nervous system apoptosis is not limited to development as it also occurs in pathological conditions (Chalmers-Redman *et al.*, 1996). As well as the evidence for apoptosis in MS presented above, it is now thought to contribute to neurodegenerative diseases including Parkinson's disease (Olanow and Tatton, 1999), Alzheimer's disease (Anderson *et al.*, 1996; Su *et al.*, 1997), amyotrophic lateral sclerosis (Yoshiyama *et al.*, 1994), Huntington's disease (Thomas *et al.*, 1995) as well as acquired immunodeficiency syndrome (AIDS) (Petito and Roberts, 1995). Participation of apoptosis in those conditions was largely missed on standard neuropathological examination due to the absence of inflammation and the selective culling of scattered cells.

1.4.1 The Differentiation of Apoptosis and Necrosis

The occurrence of differences in the ultrastructure of cells dying by apoptosis or necrosis was first observed by Kerr who recognized a subpopulation of cells in the ischemic liver that were shrunken and retained intact lysosomal structure (Kerr, 1965). In

ischemic liver that were shrunken and retained intact lysosomal structure (Kerr, 1965). In contrast, necrotic hepatic cells were swollen with dissolution of lysosomes. Electron microscopy revealed that the shrunken cells had undergone cytoplasmic condensation and budding into membrane bound cell fragments, which were engulfed by phagocytes. Importantly, organelle structure was maintained within the cell fragments (Kerr, 1971).

In 1972, Kerr, Wyllie and Currie (Kerr *et al.*, 1972) detailed the ultrastructural features of the shrunken cells and termed the process as "apoptosis". They reported that the nuclei showed chromatin condensation and segregation into sharply delineated masses. They termed the condensed and fragmented cytoplasm that was membrane-wrapped as apoptotic bodies. The picture of apoptosis is slightly different *in vitro* where, in the absence of macrophages, apoptotic bodies persist for a longer period of time and may undergo cytolysis or secondary necrosis.

In 1980, Wyllie reported that the activation of endonucleases in apoptosis resulted in nuclear DNA fragmentation (Wyllie, 1980). Gel electrophoresis showed a 180-200 bp "ladder" pattern of DNA degradation indicative of internucleosomal DNA cleavage. DNA fragments of 300 or 500 bp in length are also formed in apoptosis and can be better detected with pulse field techniques (Sestili *et al.*, 1996). In contrast, in necrosis DNA cleavage is random producing a diffuse smear on DNA electrophoresis.

However, large amounts of tissue are required to detect DNA cleavage with these techniques, so they are not suitable for detecting small numbers of apoptotic nuclei and in a tissue with a number of different cell types, they do not allow the investigator to determine which types are apoptotic and which types are not. Nuclear DNA cleavage can be detected *in situ* using end labeling (ISEL) techniques, which attach a chromagen or

fluorochrome to the 3' cut ends of DNA (Migheli *et al.*, 1994; Tatton and Kish, 1997).

Chromatin condensation, which accompanies DNA fragmentation, can also be detected *in situ* staining with fluorescent DNA binding dyes such as acridine orange, Hoechst 33258 or YOYO-1 (Darzynkiewicz *et al.*, 1992; Tatton and Kish, 1997). Apoptosis can be unambiguously demonstrated if DNA ladder, ISEL positive nuclei and nuclear chromatin condensation are jointly demonstrated for the same cells.

1.4.2 Nerve Cell Apoptosis

It is now known that the massive death of neurons that occurs during mammalian prenatal and postnatal brain development depends on competition for trophic factors and represents a form of apoptosis (Martin *et al.*, 1992; Raff *et al.*, 1993). Nerve cells obtain their trophic support from their targets, which can supply limited amounts of trophic molecules. Limited supply of trophic molecules leads to a competition among the developing neurons so that neurons that are best connected survive while weakly connected neurons die (Oppenheim, 1991). The trophic insufficiency dependent death of developing neurons was termed "programmed cell death" since it depended on activation of a program of gene expression that led to the synthesis of "death proteins" (Oppenheim *et al.*, 1990).

A requirement for new protein synthesis can be a hallmark of programmed neuronal death or apoptosis, although it is not necessary for all forms of neuronal apoptosis (Dragunow and Preston, 1995; Johnson *et al.*, 1995). In some forms of neuronal apoptosis, proteins that are necessary for apoptosis to occur are constitutively expressed, while they must be newly synthesized in others (Eastman, 1993). The characteristic

morphologic findings of apoptosis persist in many models of nerve cell apoptosis, even when transcriptional and translational blockers are used to inhibit new protein synthesis. For example, transcriptional or translational blockers that greatly reduce new protein synthesis do not prevent apoptosis after serum withdrawal in PC12 cells that have been exposed to serum but not to NGF (Rukenstein *et al.*, 1991). Similarly, PC12 cells that have been exposed to NGF for 6 days and have initiated process growth, undergo apoptosis after serum and NGF withdrawal that is independent of new protein synthesis (Tatton *et al.*, 1994). In contrast, apoptosis in neuronally-differentiated PC12 cells caused by trophic withdrawal after 9-12 days of NGF exposure requires new protein synthesis (Mesner *et al.*, 1992). Therefore, apoptosis can be dependent on new protein synthesis and be termed programmed cell death, or can be independent of new protein synthesis and be unprogrammed. Dependence on new protein synthesis can be used as a marker for neuronal apoptosis (Sanchez *et al.*, 1997; Ueda *et al.*, 1996) but absence of new protein synthesis does not rule out apoptosis (Deshpande *et al.*, 1992).

1.4.3 Changes In Gene Expression and Protein Levels in Apoptosis

In recent years, a number of genes and their protein products have been found to mediate the progression of apoptosis. Such genes and protein products can serve as markers of apoptotic cell death process. Included among mediators of apoptosis are oncoproteins, oncogenes, and several protease families. The BCL-2 homolog family of oncoproteins includes both inhibitors and promoters of apoptosis (Hockenberry, 1992; Merry and Korsmeyer, 1997). Inhibitors of apoptosis include BCL-2 itself, BCL-X (BCL-X_L, BCL-X_α, and BCL-X_β), MCL-1, and A1, while BAX, BCL-X_S, BAD, BAK, and

BIK promote apoptosis. Some of the BCL-2 family members like BCL-2 and BAX can also interact with each other by forming homo- or heterodimers. Most of the oncoproteins are found localized to the outer mitochondrial and nuclear membranes. In normal hemopoietic cells, BCL-2 is concentrated in the outer mitochondrial membrane, while BAX is largely confined to the cytosol however during apoptosis BAX becomes concentrated in mitochondrial membranes (Hsu *et al.*, 1997). Furthermore, in the early stages of apoptosis, a number of cytoplasmic proteins undergo nuclear translocation.

A number of proteases, including cysteine proteases, calpains, and proteasomes have been shown to be involved in the apoptotic cell death process. Most recent research efforts have been focused on the interleukin converting enzyme (ICE)-like proteases which are termed caspases (Cohen, 1997; Nath *et al.*, 1996). To date, 10 different caspases have been identified with caspase-3 receiving most attention (Krajewska *et al.*, 1997). The caspases are synthesized as inactive precursors and are activated in models of neuronal apoptosis (Armstrong *et al.*, 1997; Du *et al.*, 1997). Other proteases like calpains have been shown to contribute to the cleavage of the cytoskeletal protein actin during apoptosis (Brown *et al.*, 1997). Calpain inhibitors have been shown to block actin cleavage in apoptosis (Gressner *et al.*, 1997).

Cell-cycle related proteins and cycle kinases including cyclin D1, cyclin B, cyclin E, and Cdc2 kinase show increased levels during neuronal apoptosis (Freeman *et al.*, 1994; Gao and Zelenka, 1995; Haupt *et al.*, 1996; Kranenburg *et al.*, 1996). Appearance of the cycle-related proteins is thought to represent an abortive attempt of the post mitotic neuronal cells to return to the cell cycle (Shirvan *et al.*, 1997).

Another protein involved in the cell cycle as a mitosis inhibitor, p53, increases in

a number of forms of neuronal apoptosis (Jordan *et al.*, 1997; Polyak *et al.*, 1997) and has been shown to increase the levels of the oncoprotein BAX in non-neuronal forms of apoptosis (Xiang *et al.*, 1998). It is now understood that apoptosis can be separated into p53 dependent and p53 independent forms (see (Bellamy, 1997) for a detailed review of the role of p53 in apoptosis). Recently, a large number of p53-induced genes (PIGs) have been identified, which are proposed to mediate apoptosis by increasing oxidative radical levels, thereby inducing mitochondrial damage (Polyak *et al.*, 1997). p53-induced apoptosis can proceed after treatment with translational or transcriptional blockers (Kharlamov *et al.*, 1997), indicating that p53 can induce apoptosis through pathways that do not require new protein synthesis.

A signal-transducing transcription factor of the AP-1 family, c-jun, is normally involved in cell cycle control and differentiation. A variety of evidence indicates that c-JUN is involved in a number of *in vitro* and *in vivo* models of neuronal apoptosis (Bossy-Wetzel *et al.*, 1997). Apoptosis is also induced by the Fas antigen and its mRNA has been shown to increase in ischemic nerve and glial cells (Depraetere and Golstein, 1997; Matsuyama *et al.*, 1995). Another marker for apoptosis is tissue transglutaminase, which cross-links cytoplasmic proteins and is increased in apoptotic cells (Fesus *et al.*, 1991). Transglutaminase activity leads to the formation of high molecular mass protein polymers, which maintain the integrity of apoptotic cells and bodies and prevents leakage of their contents into the extracellular space.

Lastly, overexpression of the gene for the radical scavenger protein, Cu/Zn superoxide dismutase (SOD-1), reduces neuronal apoptosis (Greenlund *et al.*, 1995; Przedborski *et al.*, 1992) while underexpression increases apoptosis (Troy and Shelanski,

1994). Point mutations in the gene that encodes SOD-1 has been shown to convert the anti-apoptotic action of SOD-1 to a pro-apoptotic one (Rabizadeh *et al.*, 1995).

1.4.4 The Role of Mitochondria in Apoptosis

Mitochondria are now believed to play a critical role in signaling for the initiation of some forms of apoptosis. Apoptosis was initially believed to occur independently of mitochondrial factors (Jacobson *et al.*, 1993; Korsmeyer *et al.*, 1993). The importance of mitochondria in the initiation of apoptosis is illustrated by the finding that mitochondrial factors can induce chromatin condensation and nuclear fragmentation typical of apoptosis in cell free *Xenopus* egg extracts (Newmeyer *et al.*, 1994). Current evidence now indicates that apoptosis is associated with a sequence of events that includes a fall in mitochondrial membrane potential ($\Delta\Psi_M$), opening of a mitochondrial megapore known as the permeability transition pore (PTP), and release into the cytoplasm of small mitochondrial proteins which signal the initiation of apoptosis known as apoptosis initiating factors (AIF).

1.4.5 Mitochondrial Membrane Potential And Apoptosis

Studies of $\Delta\Psi_M$ have been pivotal in understanding the relationship between mitochondria and the initiation of apoptosis. An electrochemical proton gradient normally exists across the inner mitochondrial membrane resulting in a $\Delta\Psi_M$ of approximately -150 millivolts and a proton concentration difference (ΔpH) across the mitochondrial membrane. The $\Delta\Psi_M$ is dependent on the capacity of mitochondrial complexes I, III, and

IV to use electron energy in the carrier molecules nicotinamide adenine dinucleotide (NADH), ubiquinone, and cytochrome C (CytC) to pump protons out of the mitochondrial matrix by transporting them across the inner mitochondrial membrane. Complex II transfers energy from FADH₂ to ubiquinone, but does not pump protons. The outward pumping of protons produces an electron gradient that is biochemically reflected by a pH difference (ΔpH) and electrically by a voltage across the inner mitochondrial membrane also known as $\Delta\Psi_M$ (Sheratt, 1991). The $\Delta\Psi_M$ and the ΔpH contribute to a proton electromotive force (δp) ($\delta p = \Delta\Psi - 60 \Delta\text{pH}$, where ΔpH = mitochondrial pH - cytosol pH). δp drives the conversion of ADP to ATP at complex V (ATP synthase). Since $\Delta\Psi_M$ is by far the greater contributor to δp , $\Delta\Psi_M$ can be assumed to vary almost linearly with the ATP/ADP ratio and to provide an estimate of the ATP/ADP ratio within individual mitochondria.

Measurements of whole cell potentiometric dye fluorescence in a variety of blood, hepatic, and immune cell models have shown that $\Delta\Psi_M$ is reduced very early in the apoptotic process, prior to the onset of nuclear DNA fragmentation and chromatin condensation (Susin *et al.*, 1996). More recently, Tatton and coworkers used laser confocal imaging to obtain direct measurements of $\Delta\Psi_M$ in living NGF-differentiated PC12 cells and showed that a decrease in $\Delta\Psi_M$ is also one of the earliest, if not the earliest, detectable event in apoptosis induced by NGF and serum withdrawal (Wadia *et al.*, 1998). $\Delta\Psi_M$ was significantly reduced in a proportion of mitochondria three to six hours prior to nuclear DNA fragmentation and chromatin condensation. The decrease in

$\Delta\Psi_M$ was temporally correlated with an increase in intramitochondrial Ca^{2+} but not with an increase in cytosolic oxidative radical levels, which increased only after the decrease in $\Delta\Psi_M$ was well established. Decreases in $\Delta\Psi_M$ coupled with increases in intramitochondrial Ca^{2+} induce opening of the PTP (see below (Scorrano *et al.*, 1997). Accordingly, these changes found in early apoptosis were appropriate to open the PTP.

1.4.6 The Permeability Transition Pore

A decrease in $\Delta\Psi_M$, in the presence of increased intramitochondrial Ca^{2+} (Scorrano *et al.*, 1997), induces opening of a PTP, which spans the inner and outer mitochondrial membranes. The PTP consists of an adenine nucleotide translocator (AdNT) which is a critical element of the PTP but whether it forms the pore itself or is just closely associated with a pore forming protein is unknown. The PTP also includes a voltage dependent anion channel (a porin) and a peripheral benzodiazepine binding protein. The components of the PTP are closely associated with hexokinase, creatine kinase, and BCL-2, as well as other elements, such as glycerol kinase, phospholipid hydroperoxidase, glutathione peroxidase, 3-b-hydroxysteroid dehydrogenase isomerase, and cardiolipin synthase.

The PTP opens in response to a decrease in $\Delta\Psi_M$ in the presence of an increase in intramitochondrial Ca^{2+} (Scorrano *et al.*, 1997). Marked increases in mitochondrial Ca^{2+} , increased oxidative radical levels, or partial failure of the respiratory complexes, acting either individually or together, can induce a fall in $\Delta\Psi_M$ (Richter, 1993). Opening of the PTP dissipates any remaining proton gradient across the mitochondrial membrane and

further reduces the $\Delta\Psi_M$ (Bernardi *et al.*, 1994). Complete opening of the PTP allows free exchange of solutes and small proteins between the mitochondrial matrix and the extramitochondrial cytosol. Consequently mitochondria swell rupturing the outer mitochondrial membrane. As a result AIFs are released from the intermembrane space of the mitochondria into the cytoplasm (Marchetti *et al.*, 1996; Susin *et al.*, 1996).

Mitochondrial AIFs may be released directly through the PTP or through fractures in the mitochondrial membrane.

Several factors are known to influence opening or closure of the PTP. Compounds like cyclosporin A bind to the PTP and maintains it in a closed position. It also promotes pore closure by binding cyclophilins that otherwise induce PTP opening in the presence of Ca^{2+} by binding to the AdNT (Bernardi *et al.*, 1994; Scorrano *et al.*, 1997). Factors like glutathione, ADP levels, and ROS levels in the mitochondrial matrix modulate the gating voltages necessary to induce PTP opening but are not sufficient in themselves to open the PTP (Chernyak and Bernardi, 1996).

Anti-apoptotic proteins like BCL-2 bind to the PTP. BCL-2 binds to the peripheral benzodiazepine binding component of the mitochondrial PTP (Carayon *et al.*, 1996) and maintains closure of the PTP in a manner similar to cyclosporin A. BCL-2 has been shown to localize to the outer mitochondrial membrane (Lithgow *et al.*, 1994; Riparbelli *et al.*, 1995) within or near to, the mitochondrial peripheral benzodiazepine receptor (Carayon *et al.*, 1996). Cytosolic BCL-2, which is truncated and cannot dock in mitochondrial membranes, is considerably less effective in reducing apoptosis than BCL-2 located in mitochondrial membranes (Hockenberry *et al.*, 1993). Richter first proposed that BCL-2 reduces apoptosis by maintaining $\Delta\Psi_M$ (Richter, 1993). Zamzami and

coworkers subsequently provided persuasive evidence, demonstrating that BCL-2 maintains PTP closure (Zamzami *et al.*, 1996) and blocks the initiation of apoptosis by preventing the escape of heat labile molecules, which signal the onset of apoptosis. Numerous other studies have also shown that BCL-2 can prevent a decrease in $\Delta\Psi_M$ and the release of ICE-like AIFs (Marchetti *et al.*, 1996; Susin *et al.*, 1996). Thus, opening of the PTP can be viewed as the critical decisional step in many forms of apoptosis and is proposed to constitute an irreversible step in the process.

1.4.7 Apoptosis Initiating Factors

The importance of mitochondrial factors in the initiation of apoptosis has been demonstrated by studies showing that mitochondrial homogenates are essential for the progression of the nuclear changes of apoptosis in cell free systems (Newmeyer *et al.*, 1994). Several apoptosis promoting mitochondrial AIFs have been identified to date. dATP, when accompanied by holocytochrome C, a nuclearly encoded 14 kDa protein, which is normally localized to the mitochondrial intermembranous space, can promote apoptosis in some cell free systems (Liu *et al.*, 1996). Additionally, in some forms of apoptosis, CytC can be found in the extramitochondrial cytosol in the early stages of apoptosis (Yang *et al.*, 1997) and injection of CytC into cells induces apoptosis (Li *et al.*, 1997). CytC release from mitochondria has been shown to activate a caspase 3 precursor leading to activation of an endonuclease that cleaves nuclear DNA (Kharbanda *et al.*, 1997; Li *et al.*, 1997).

1.4.8 Oxidant Radicals and Mitochondrial Apoptosis

An increase in oxidative radicals derived from the mitochondria is thought to be associated with mitochondrial apoptosis (Richter *et al.*, 1995). Increased levels of oxidative radicals, particularly in the presence of increased intramitochondrial Ca^{2+} , can induce apoptosis by causing cross linking of protein thiols in the mitochondrial inner membrane (van de Water *et al.*, 1994) and opening of the PTP (Chernyak and Bernardi, 1996). BCL-2 which has been shown to act as an anti-oxidant is thought to provide anti-apoptotic effects through an indirect effect on the PTP as well as by its direct effect on the PTP (Hockenberry *et al.*, 1993). Tatton and his co-workers have shown that a decrease in BCL-2 levels in trophically-deprived PC12 cells entering mitochondrial apoptosis is associated with markedly increased cytosolic levels of oxidative radicals (Tatton *et al.*, 1996). In contrast, the reduction in apoptosis induced by bcl-2 overexpression is associated with a decrease in both oxidative radical levels and in peroxidation of membrane lipids (Hockenberry *et al.*, 1993). Similar effects have been detected with oxidative radical scavengers, such as SOD-1 and glutathione, which have been shown to prevent the direct action of oxidative radicals on PTP opening (Chernyak and Bernardi, 1996). These direct and indirect actions of oxidative radicals on the PTP may reinforce each other in inducing apoptosis.

1.5 (-)-Deprenyl Can Reduce Apoptosis

(-)-Deprenyl is a selective inhibitor of monoamine oxidase B (MAO-B) (Heinonen *et al.*, 1994). Co-administration of (-)-deprenyl or other MAO-B inhibitors with the parkinsonian toxin, 1-methyl-4-phenyl -1,2,3,6-tetrahydropyridine (MPTP)

reduced the decreases in striatal dopaminergic indices caused by the toxin alone (Cohen *et al.*, 1984; Heikkila *et al.*, 1984; Langston *et al.*, 1984). The reduction was interpreted to depend on the blockade of the conversion of MPTP to its active radical, MPP⁺, by MAO-B in astroglia. If MPTP could not be converted to MPP⁺, then it could not induce necrosis of substantia nigra dopaminergic neurons (SNDns). Necrosis of SNDns results in the loss of their striatal dopaminergic terminal axons and a decrease in striatal dopaminergic indices. Accordingly, the maintenance of the striatal dopaminergic indices was interpreted as showing that (-)-deprenyl reduced the necrosis of SNDns caused by MPP⁺.

Subsequently, it was found: 1) that (-)-deprenyl reduced the death of cultured dopaminergic neurons caused by MPP⁺ (Mytilineou and Cohen, 1985), 2) that (-)-deprenyl reduced the loss of murine SNDns when (-)-deprenyl treatment was delayed until after the conversion of MPTP to MPP+ was completed (Tatton and Greenwood, 1991) or when (-)-deprenyl doses were employed that were insufficient to inhibit MAO-B or MAO-A (Tatton *et al.*, 1993) and 3) that (-)-deprenyl could increase the survival of non-dopaminergic neurons and axotomized motoneurons, independently of MAO inhibition (Ansari *et al.*, 1993; Salo and Tatton, 1992). Those studies established that (-)-deprenyl could increase neuronal survival through a mechanism that did not require the inhibition of MAO-B.

Studies in trophically-withdrawn neuronally differentiated PC12 cells (Tatton *et al.*, 1994), cerebellar granule cells exposed to cytosine arabinoside (Paterson *et al.*, 1998), trophically deprived human melanoma cells (Magyar *et al.*, 1998) and dopaminergic MES23.5 cells exposed to MPP+ (Le *et al.*, 1997) showed that (-)-

deprenyl can reduce apoptotic cell death. Since the original reports of MAO-B independent neuronal rescue, more than thirty studies have reported reduced nerve cell death by (-)-deprenyl for a variety of different types of neurons including motoneurons (Ansari *et al.*, 1993; Iwasaki *et al.*, 1996; Ju *et al.*, 1994; Oh *et al.*, 1994; Ravikumar *et al.*, 1998; Salo and Tatton, 1992; Zhang *et al.*, 1995), neuronally differentiated PC12 cells (Tatton *et al.*, 1994), retinal cells (Buys, 1995; Ragaiy *et al.*, 1997), inferior olivary neurons (Todd and Butterworth, 1998), inferior collicular neurons (Todd and Butterworth, 1998), thalamic neurons (Todd and Butterworth, 1998), mesencephalic dopaminergic neurons (Koutsilieri *et al.*, 1996; Koutsilieri *et al.*, 1994; Mytilineou *et al.*, 1997; Wu *et al.*, 1995), cerebellar neurons (Paterson *et al.*, 1998), cortical neurons (Amenta *et al.*, 1994), striatal neurons (Vizuete *et al.*, 1993) and hippocampal neurons (Amenta *et al.*, 1994; Knollema *et al.*, 1995; Lahtinen *et al.*, 1997; Paterson *et al.*, 1997; Semkova *et al.*, 1996; Zeng *et al.*, 1995; Zhang *et al.*, 1996). Increased neuronal survival has been found after a wide variety of different insults including trophic withdrawal (Tatton *et al.*, 1994), MPP⁺ exposure (Koutsilieri *et al.*, 1996; Koutsilieri *et al.*, 1994; Schmidt *et al.*, 1997; Wu *et al.*, 1995), excitotoxicity (Abakumova *et al.*, 1998; Kiran *et al.*, 1998; Mytilineou *et al.*, 1997; Semkova *et al.*, 1996), ischemia or hypoxia (Knollema *et al.*, 1995; Lahtinen *et al.*, 1997; Paterson *et al.*, 1997; Ravikumar *et al.*, 1998), DNA toxins (Paterson *et al.*, 1998), axotomy (Ansari *et al.*, 1993; Buys, 1995; Ju *et al.*, 1994; Oh *et al.*, 1994; Salo and Tatton, 1992; Zhang *et al.*, 1995), thiamine deficiency (Todd and Butterworth, 1998), and catecholaminergic toxins (Zhang *et al.*, 1996).

(-)-Deprenyl has not been universally effective in reducing cell death (Ballabriga *et al.*, 1997; Fang *et al.*, 1995; Rothblat and Schneider, 1998; Thiffault *et al.*, 1997;

Vaglini *et al.*, 1996). In some cases, (-) -deprenyl has been found to be highly effective or ineffective in reducing neuronal death in similar models. For example, three groups exposed adult gerbils to 5 minutes of bilateral carotid occlusion and began daily (-) - deprenyl treatment at 1-2 hours after the occlusion. One group evaluated CA1 hippocampal neuronal numbers at day 4 after daily treatment with 10 mg/kg (-) - deprenyl and found no increase in survival (Ballabriga *et al.*, 1997). The other evaluated CA1 hippocampal neuronal numbers at days 3 or 7 after treatment with 0.25 mg/kg and found a significant increase in survival at both time points (Lahtinen *et al.*, 1997). A third group evaluated 0.25 mg/kg daily (-)-deprenyl treatment on hypoxia/ischemia induced rat CA1, CA3 and CA4 hippocampal neuronal death at multiple time points up to 14 days and found markedly significant increases in neuronal survival (Paterson *et al.*, 1997).

Three different factors have been proposed to account for models in which (-)-deprenyl is ineffective: 1) that (-) -deprenyl can only reduce neuronal death mediated by apoptosis but not that mediated by necrosis. For example high levels of MPTP or MPP⁺ induce necrosis while lower levels induce apoptosis (Hartley *et al.*, 1994; Mochizuki *et al.*, 1994; Spooren *et al.*, 1998; Tatton *et al.*, 1997). The levels of MPTP or MPP⁺ that were employed may explain studies in which (-)-deprenyl was effective (Koutsilieri *et al.*, 1996; Koutsilieri *et al.*, 1994; Mytilineou and Cohen, 1985; Schmidt *et al.*, 1997; Tatton and Greenwood, 1991; Tatton *et al.*, 1993; Wu *et al.*, 1995) versus those in which it was ineffective (Rothblat and Schneider, 1998; Thiffault *et al.*, 1997; Vaglini *et al.*, 1996). Similar variability in the rapidity and depth of hypoxia may account for the variable effectiveness of (-)-deprenyl in hypoxia/ischemia models considered above. 2)

that (-)-deprenyl may only be effective in some forms of apoptosis but not in other forms. Paterson showed that (-)-deprenyl reduced apoptosis of cultured cerebellar granule cells induced by cytosine arabinoside but not that induced by low potassium levels (Paterson *et al.*, 1998). Similar our group has found that (-)-deprenyl reduces apoptosis in PC12 cell that have been exposed to serum and NGF (Tatton *et al.*, 1994; Wadia *et al.*, 1998) but not those that have only been exposed to serum (Chalmers-Redman and Tatton , unpublished observations). Similarly, (-)-deprenyl does not reduce apoptosis in the classic model of dexamethasone-exposed lymphocytes (Fang *et al.*, 1995). Paterson (Paterson *et al.*, 1998) has proposed that (-)-deprenyl only reduces those forms of apoptosis that involve a mitochondrial decision point (see above). For example, cytosine arabinoside induced apoptosis of cerebellar granule cells involves an early decrease in $\Delta\Psi_M$ while apoptosis induced by low potassium in the same cells does not involve early decreases in $\Delta\Psi_M$. (-)-Deprenyl is effective in the former but not the latter. Similarly, apoptosis in PC12 cells exposed to serum and NGF involves an early decrease in $\Delta\Psi_M$ and is responsive to (-)-deprenyl (Wadia *et al.*, 1998) while that in PC12 cells that have only been exposed to serum does not involve an early decrease in $\Delta\Psi_M$ and is unresponsive to (-)-deprenyl (Chalmers-Redman and Tatton , unpublished observations). Lastly, dexamethasone induced lymphocyte apoptosis does not involve an early decrease in $\Delta\Psi_M$ (Zamzami, personal communication) and is not (-)-deprenyl responsive. Accordingly, those forms of apoptosis that do involve an early decrease in $\Delta\Psi_M$ may not respond to (-)-deprenyl. 3) Recently, it has been suggested, but not proven, that the primary metabolite of (-)-deprenyl, (-)-desmethyldeprenyl (DES),

mediates anti-apoptosis rather than (-)-deprenyl itself (Mytilineou *et al.*, 1997).

Accordingly, variations in (-)-deprenyl effectiveness from model to model may depend on the tissues capacity to convert (-)-deprenyl to DES.

1.5.1 (-)-Deprenyl Requires New Protein Synthesis To Reduce Apoptosis And Alters Gene Expression And Protein Synthesis In Pre-Apoptotic Cells

Studies in neuronally-differentiated PC12 cells showed that transcriptional inhibition by actinomycin and translational inhibition by cycloheximide or camptothecin blocked the capacity of (-)-deprenyl to reduce apoptosis in the cells (Tatton *et al.*, 1994). In a variety of cell types, (-)-deprenyl has been shown to increase gene expression, protein levels or protein activity for superoxide dismutases (SOD1 and SOD2) (Carrillo *et al.*, 1991; Kitani *et al.*, 1994; Li *et al.*, 1998; Thiffault *et al.*, 1995), BCL-2 (Tatton and Chalmers Redman, 1996), heat shock protein 70 (Lahtinen *et al.*, 1997; Zhang *et al.*, 1996), GFAP (Amenta *et al.*, 1994; Biagini *et al.*, 1994; Biagini *et al.*, 1993; Ju *et al.*, 1994; Li *et al.*, 1993; Revuelta *et al.*, 1997), aromatic amino acid decarboxylase (Li *et al.*, 1992), tyrosine hydroxylase (Li *et al.*, 1997; Reinhard and JP, 1991; Rodriguez-Gomez *et al.*, 1997), CNTF (Seniuk *et al.*, 1994), NGF (Li *et al.*, 1997; Semkova *et al.*, 1996), FGF (Biagini *et al.*, 1994), and trk receptor (Ekblom *et al.*, 1994).

It is not known whether any of the above proteins are associated with the capacity of (-)-deprenyl to reduce apoptosis. SOD1 underexpression increases apoptosis while its overexpression decreases apoptosis in PC12 cells and sympathetoblasts (Greenlund *et al.*, 1995; Troy and Shelanski, 1994) making an increase in SOD1 expression a candidate

for the anti-apoptotic effects of (-)-deprenyl. The capacity of (-)-deprenyl to increase SOD1 has been shown to vary from tissue to tissue (Carrillo *et al.*, 1992; Lai *et al.*, 1994), which might also explain the variability in (-)-deprenyl effectiveness. BCL-2 may also contribute to (-)-deprenyl anti-apoptosis. BCL-2 has been shown to prevent the fall of $\Delta\Psi_M$ that is characteristic of some forms of apoptosis (Kroemer *et al.*, 1997; Susin *et al.*, 1996) and (-)-deprenyl also prevents a fall in $\Delta\Psi_M$ in neuronally differentiated PC12 cell (Wadia *et al.*, 1998) and cerebellar granule cell apoptosis (Paterson *et al.*, 1998). A decrease in BCL-2 levels has been shown to contribute to the fall in $\Delta\Psi_M$ in apoptotic cells (Kroemer *et al.*, 1997; Susin *et al.*, 1996) while a maintenance of BCL-2 through its new synthesis would prevent a fall in $\Delta\Psi_M$ and the initiation of apoptosis.

It has been suggested that the anti-apoptotic action of (-)-deprenyl on neurons is mediated by the capacity of the compound to increase the synthesis of CNTF (Seniuk *et al.*, 1994), NGF (Semkova *et al.*, 1996) and bFGF (Biagini *et al.*, 1994) by astrocytes (Koutsilieri *et al.*, 1996). According to that proposal, (-)-deprenyl would increase the provision of trophic support to damaged neurons on astroglia and thereby reduce apoptosis.

It is not known whether (-)-deprenyl or one or more of its metabolites can influence apoptosis in oligodendroglial cells. Furthermore, it is not known whether any effects of (-)-deprenyl on oligodendroglial cells involves new protein synthesis and/or whether (-)-deprenyl has any effect on $\Delta\Psi_M$ in the cells.

1.6 Specific Aims

1. To establish a tissue culture model system to study whether IGF-I and insulin withdrawal causes apoptosis in differentiated cells of the O-2A cell lineage like the PROLs and OLs similar to that observed in the progenitor cell population.

Primary cultures of oligodendrocytes will be established by obtaining purified populations of O-2A progenitor cells isolated from the rat cerebral cortex and differentiating them in the presence of trophic factors, insulin and IGF-I. The different cell types of the O-2A lineage will be identified on the basis of morphological and immunocytochemical criteria. Apoptotic degradation will be studied using multiple complementary approaches including a) staining of chromatin with fluorescent DNA binding dyes; b) gel electrophoresis of DNA and c) *in situ* end labeling (ISEL) of nicked 3' ends of DNA.

2. To determine the time course of any apoptotic death of the insulin and IGF-I withdrawn PROLs and OLs.

An estimate of the time course of cell death will be obtained from counts of ISEL positive apoptotic nuclei of PROLs and OLs after 6, 12, 15, 18 and 24 h after withdrawal of insulin and IGF-I.

3. To determine whether (-)-deprenyl can reduce apoptosis in PROLs and OLs.

The effects of (-)-deprenyl on cell survival will be determined by obtaining nuclear and cell counts. The numbers of ISEL positive nuclei will also be examined to determine whether they are appropriately reciprocal to the cell numbers. DNA electrophoresis gels will be used to determine whether (-)-deprenyl eliminates or reduces DNA "laddering" at appropriate time points.

4. To determine whether any anti-apoptotic effects on the PROLs and the OLs are brought about by (-) -deprenyl itself or by one of its metabolites, like (-) -desmethyldeprenyl.

The intact nuclear count method will be used to quantify the effects of the metabolites of (-) -deprenyl on the survival of the PROLs and the OLs. Three general cytochrome P450 blockers will be used to determine if the blocking of metabolism of (-)-deprenyl or a metabolite eliminates any increased PROL and OL survival induced by the compound.

5. To determine whether any anti-apoptotic action of (-)-deprenyl and /or an active metabolite requires new protein synthesis by using actinomycin D to inhibit transcription and cycloheximide to inhibit translation.

6. To determine whether (-)-deprenyl or an active metabolite modifies the levels of PROL and OL specific proteins.

Western blot analysis of individual proteins will be used to analyze changes in the levels of PROL and OL specific proteins.

7. To determine whether a decrease in $\Delta\Psi_M$ is involved in any OL and PROL apoptosis induced by IGF-I and insulin withdrawal.

The involvement of mitochondria in the apoptotic death of PROLs and OLs will be determined using $\Delta\Psi_M$ changes as an indicator. The mitochondrial potentiometric dye, chloromethyltetramethyl rosamine (CMTMR) will be imaged in individual mitochondria in intact cells using confocal laser microscopy.

8. To determine whether treatments with (-)-deprenyl or an active metabolite or those

that block decreases in any apoptosis in PROLs and OLs have appropriate actions on
 $\Delta\Psi_M$.

2.0 Materials and Methods

2.1.1 Preparation of Mixed Primary Glial Cultures

Primary cultures enriched in O-2A progenitors grown over a monolayer of astrocytes were derived from the cerebral cortex of 2-day-old rat pups. Timed pregnant Sprague Dawley rats (Charles River, Montreal, Canada) were obtained at 18 days gestation and housed in the Carleton Animal Care Facility at Dalhousie University. Two litters (consisting of about 10-12 pups / litter), obtained at postnatal day 2, were used in each experiment. The rat pups were anesthetized with a brief exposure to an inhalant anesthetic, Metofane and then quickly decapitated. Using sterile technique, the skull was opened via the foramen magnum towards the olfactory bulb and the skull flaps were pried open carefully. With a microspatula, the entire brain was lifted away and placed in cold Dulbecco's modified Eagle's medium (DMEM; GibcoBRL, Life Technologies, Ontario, Canada) supplemented with 15% fetal bovine serum (FBS; Hyclone Laboratories Inc, Utah, USA). Subsequently, the meninges were removed and the cerebral hemispheres transferred to another sterile petridish. The cerebral hemispheres were then dissected under a stereomicroscope and the cortices isolated free of the midbrain, hippocampus and the striatum. Using a cell scraper all the neocortical tissue was mechanically dissociated and filtered successively through 210 and 130 μm Nitex meshes (B&SH Thompson & Co Ltd, Ontario, Canada). This procedure allows for the elimination of contaminating fibroblasts. The cell suspension was centrifuged at 300 x g in 50 ml tubes using a Sanyo Mistral 3000i centrifuge and the cells pelleted and resuspended in DMEM containing 15% serum. Viable cells, as determined by the Trypan Blue dye exclusion, were counted on a haemocytometer and plated at a density of 1.37×10^6 cells / ml onto 185 cm^2 Nunc

culture flasks.

The mixed cultures were grown for 10 days in a media containing DMEM, 15% FBS, penicillin (50 IU / ml), streptomycin (50 µg / ml), 1mM sodium pyruvate; 50 µg / ml transferrin (Sigma Chemical Co., MO, USA) ; 0.005 µg / ml sodium selenite (Sigma) and 5 µg / ml insulin (Upstate Biotechnology Inc, NY, USA) until confluent. The media was replaced every 3 days.

2.1.2 Preparation of Secondary Cultures

Secondary cultures enriched in pure populations of oligodendrocytes were obtained by a modification of the selective adhesion protocol of (McCarthy, 1980). By 10 days *in vitro* (DIV), the O-2A progenitor cells had spread in clusters over the confluent layer of astrocytes. The flasks were then subjected to a 'preshape' at 170 rpm for 1 hour, 37°C, (in order to release macrophages, dead cells and debris) on an orbital shaker (Aros 160, Thermolyne) with an inch and a quarter stroke diameter. The preshape was followed by an 18 hour shake at 230 rpm. Medium containing the detached O-2A cells was recovered and filtered through a 20 µm Nitex mesh to remove clumps of dead cells and larger type-1 astrocytes. The cell filtrate was plated for 5 min in a plastic petridish in order to separate the O-2A progenitor cells from microglia. The loosely adherent O-2A cells were detached by incubating them in a solution of 10 mM Tris and 1 mM EDTA (pH 7.4) at 37°C for 5 min. The cells were subjected to centrifugation at 300 x g for 5 min and cells were resuspended in an oligodendrocyte differentiating media (ODM)

containing DMEM, 10% FBS, 16 µg / ml putrescine (Sigma), 0.006 µg / ml progesterone (Sigma), 5 µg / ml insulin, 2.5 ng / ml insulin-like growth factor-1 (Upstate), 50 µg / ml transferrin and 0.005 µg / ml sodium selenite. The ODM was based on a modification of the defined medium as described by Hunter (Hunter and Bottenstein, 1990).

The cell suspension was plated on 12 mm and 22-mm coverslips (Assistant Glass, Carolina Biological Supply Co., Burlington, NC, USA) as well as 24 well Nunc plastic plates. The coverslips used were alkaline etched (NaOH, 0.5 N) for 30 minutes. The coverslips were then thoroughly washed with distilled water, autoclaved and subsequently poly-L-lysine (Sigma, P6282) coated. The cell suspension was plated at two different densities: 1) 5.3×10^3 cells / mm² (experimental series I) and 2) 15.8×10^3 cells / mm² (experimental series II). The cells were maintained in ODM with 10% FBS for 3 hr at 37°C to enhance survival following which the media was replaced with ODM with low serum (containing 1% FBS). The O-2A progenitors were then allowed to differentiate for a further 6 days, and monitored by phase contrast microscopy to determine when the majority of the cells could be morphologically identified as OLs. Phase contrast micrographs of the differentiating O-2A progenitors were taken using a Leitz inverted phase contrast microscope coupled to a CCD camera.

2.2 Immunocytochemical Detection of Cultured Oligodendroglial Cells

Cells growing on coverslips were identified by immunocytochemistry for specific markers of oligodendrocyte development like A2B5 (Eisenbarth *et al.*, 1979), 2'-3'-cyclicnucleotide - 3'- phosphorylase (CNPase) (Knapp, 1988), galactocerebroside (GC)

(Ranscht, 1982), myelin basic protein (MBP) (Lees, 1984) and proteolipid protein (PLP) (Bartlett *et al.*, 1988).

Cells growing on coverslips were fixed with 2% paraformaldehyde for 15 minutes at room temperature. The coverslips then washed three times with 0.1M phosphate buffered saline (PBS). Non-specific binding of protein was blocked by incubating the coverslips in 10% normal goat serum at room temperature for an hour, followed by permeabilization with 0.1% Tween-20 (Sigma) for 20 minutes at room temperature. Endogenous peroxidase was blocked by incubating the coverslips in 1% H₂O₂ for 10 minutes. Subsequently, the coverslips were incubated overnight at 4°C with primary antibodies. PROLs were identified by using a primary antibody to mouse anti CNPase (1:100; Sigma C-5922) while OLs were identified using antibodies to rabbit anti MBP (1:100; Zymed Laboratories Inc, San Francisco, CA, USA #18-0038) and rat anti PLP (1:100; Immunodiagnostics Inc, Bedford, MA, USA #9021). Astrocytes were identified by mouse anti glial fibrillary acidic protein (GFAP) (1:200; Sigma G-3893). All primary antibodies were diluted in 0.1M PBS / 1% normal goat serum / 0.1% Tween-20. In order to detect surface antigens present in O-2A progenitors (A2B5) and PROLs (GC), antibodies mouse anti A2B5 (1:100; Boehringer Mannheim, Quebec, Canada, 1300 016), rabbit anti-GC (1:50; Boehringer Mannheim, 1351 621) were applied to living cells for 30 minutes.

Following the primary antibody incubation, coverslips were washed 3 times with 0.1M PBS. Coverslips were then incubated with the appropriate biotinylated goat anti-mouse, goat anti-rabbit or goat anti-rat IgG secondary antibody (1:500; Vector Labs) at room temperature for one hour. Subsequently, after three washes with 0.1M PBS the

coverslips were incubated for 30 minutes with avidin-HRP (Elite Kit, Dimension Laboratories Inc., Missisauga, Ontario, Canada). Coverslips were washed with PBS and chromogenic detection was carried out using diaminobenzidine (DAB, 1.5 mg / ml) mixed with an equal volume of hydrogen peroxide (H_2O_2 ; 0.02% v/v) to obtain a brown reaction product within 5 min localizing the specific antigens. Coverslips were then dehydrated in ascending grade alcohol series, cleared with xylene and mounted on slides using a drop of permount.

2.3 IGF-I and Insulin Withdrawal and Culture Treatment Conditions

In order to examine insulin and IGF-I dependent survival of the cells of the oligodendroglial lineage, cells were trophically deprived for a period of 24 hours at 16 DIV. At this time in culture, the O-2A progenitor cells had differentiated into CNPase immunopositive PROLs and MBP immunopositive OLs.

Cells were trophically withdrawn by replacing the media with a serum free, chemically-defined base media (BM) lacking insulin and IGF-I (Bottenstein *et al.*, 1988). The base media consisted of DMEM supplemented with penicillin (50 IU / ml); streptomycin (50 µg / ml); 1mM sodium pyruvate; 50 µg / ml transferrin; 0.005 µg / ml sodium selenite; 16 µg / ml putrescine; 0.006 µg / ml progesterone and 0.1 mg / ml bovine serum albumin. All the cells were washed with BM twice before exposing them to individual treatment conditions. Control cells were washed and placed in BM supplemented with 2.5 ng / ml IGF-I and 5 µg / ml insulin to form the insulin media (IM).

To study the effects of trophic-like agents on the survival of oligodendroglial

enantiomers of deprenyl. The ability to induce increases in survival of oligodendroglial cells was seen restricted to R (-) -deprenyl and henceforth this enantiomer was used. Experiments involving dose response of (-) -deprenyl showed that a concentration of 10^{-9} M was most effective in increasing oligodendroglial cell survival hence this concentration of deprenyl was used in all subsequent experiments. For deprenyl treatment, cells were washed twice in BM to remove any serum borne survival factors and the media was replaced with BM supplemented with 10^{-9} M (-) -deprenyl (BM-D9). A second control group consisted of cells that were washed and placed in IM supplemented with 10^{-9} M (-) -deprenyl (IM-D9).

2.4 Assessment of Cell Survival by Nuclear Integrity Assay

Cell survival in the cultures was assessed according to the method of (Soto and Sonnenschein, 1985). After washing and treatment in BM, BM-D9, IM and IM-D9 for 24h, cells were harvested, centrifuged at 500 rpm for 5 min and the supernatant removed. Pelleted cells were then lysed with 200 μ l of 10% Zap-oglobin (Coulter Electronics, FL, USA). The lysing agent is a detergent containing solution that lyses the plasma membrane but leaves the nuclei intact. The lysed solution was collected and vortexed. A small volume (10 μ l) of the solution was removed and intact nuclei were counted using a haemocytometer. To be counted, nuclei had to show a completely intact smooth outer border. Counts of intact nuclei were pooled for three or four experiments (a total of 15-20 wells were used for each treatment condition).

each treatment condition).

2.5 Morphological Identification by Methylene Blue Staining and Cell Counts

Methylene blue (3, 7-bis (dimethylamino)-phenothiazin-5-iun chloride), a ribonucleic acid (RNA) binding agent commonly used as an alternative nucleic acid stain, can also be used as a biological staining agent to stain cells in order to observe their morphological features. At 24h, cells were fixed in 2% paraformaldehyde for 15 min at room temperature. Briefly, cells were washed twice with PBS and 100 μ l of 1% methylene blue (Mallinckrodt Chemical Co., MO, USA) solution containing 1% AgNO₃ was added for 10 min to the wells containing coverslips. Subsequently, the coverslips were washed with two changes of distilled water and absolute ethanol, cleared with xylene and mounted on slides with permount.

Cell counts were performed for 25 randomly chosen 100 power fields on each coverslip. Two randomly generated coordinates drawn from a uniform distribution of random numbers specified the center of each field. The random numbers were generated on a computer by using Microcal Origin 4.0 program. Comparison of the counts found by the random method to counts of all the cells on a given slide revealed differences of less than +/- 3%. Three coverslips was counted for each treatment condition. In subsequent experiments, different cell types (for example, O-2A progenitors, PROLs, OLs and astrocytes) were morphologically identified on each field and were counted separately for experimental series- I and II. Interference contrast images of the four oligodendroglial lineage cell types were obtained using a Leitz orthoplan microscope and Metamorph software program (Universal Imaging, PA, USA).

2.6 Nuclear Chromatin Staining with Hoechst 33258

Apoptosis and necrosis can be distinguished on the basis of changes in nuclear chromatin. Light microscopic studies have shown that the characteristic ultrastructural event during apoptotic cell death is the formation of phase dark, crescent shaped and marginated masses of nuclear chromatin (Wyllie, 1987). Necrotic cells on the other hand, show irregular and ill-defined chromatin. Chromatin in necrotic cell death eventually scatters into many loosely associated particles, a phenomenon also known as karyorrhexis (Wyllie *et al.*, 1981).

In order to observe changes in nuclear chromatin during trophic withdrawal and anti-apoptotic compounds, oligodendrocytes at 16 DIV, were exposed for 24 hours to the treatment conditions as described in section 2.4. At 24h, cells were fixed with 2% paraformaldehyde for 15 minutes at room temperature and subsequently washed three times in PBS. The coverslips were then incubated with 1 µg / ml 2'-(4-hydroxyphenyl)-5-(4-methyl-1-piperazinyl)-2-5'-bi-1H-benzimidazole trihydrochloride pentahydrate (Hoechst 33258, Molecular Probes) in distilled water for 30 min to visualize nuclear chromatin.

Hoechst 33258 is a supravital bisbenzimide dye, which binds to contiguous A-T bases in DNA. The coverslips were washed three times for 5 min with PBS, mounted in glycerol and viewed with epifluorescence microscopy using 340-380 nm excitation and emission filtration of 430 nm long pass.

2.7 DNA extraction and electrophoresis

DNA was extracted from trophically withdrawn as well as trophically supported oligodendroglial cells and electrophoresed in order to determine the nature of DNA degradation. Oligodendrocytes were cultured in poly-L-lysine coated 100-mm² culture dishes at a density of 1 x 10⁶ cells per dish. At 16 DIV, the cultures were exposed to BM, BM-D9, IM and IM-D9 for 24h. The DNA was extracted following the method of Batistatou and Greene (Batistatou and Greene, 1993).

Cells were lysed with 1 ml of lysis buffer (10mM Tris, pH 8.0, 1mM EDTA, 150 mM NaCl and 0.1% SDS). The lysate was then incubated overnight at 65⁰C in 20 µg/ml proteinase K (Fisher Scientific, Montreal, Canada) to eliminate contaminating proteins. This was followed by 2-hour (37⁰C) incubation in 5 µg/ml DNase-free RNase A (Boehringer Mannheim) to digest RNA. The samples were then extracted twice with a solution of phenol, chloroform, isoamyl alcohol (25:24:1; GibcoBRL). DNA in the lysates was precipitated with 3M sodium acetate (pH 5.2) and ethanol. Subsequently the samples were centrifuged for 30 minutes at 13,000 rpm and a DNA pellet was obtained. The DNA pellet was washed in 70% ethanol and air-dried. The DNA pellet was resuspended in 20µl of TE buffer (10mM Tris, 1mM EDTA; pH 8.0) and mixed completely.

Each DNA sample (10µl) was mixed with 2 µl of loading buffer (40% Sucrose, 0.25% Bromophenol blue, 0.25% Xylenecyanol) and electrophoresed in a 1.2% agarose (in 1X TAE buffer) minigel at 55V for 1 to 1 1/2 hours. A stock solution of 1 mg / ml ethidium bromide made up to a final concentration of 0.5 µg / ml in TAE (Tris base,

acetic acid, EDTA 0.5M; pH 8.6) was used to stain the gels. The gels were photographed on a transilluminator with ultraviolet light using a Polaroid DS-34 camera. Images of the films obtained from the electrophoresis gels were digitized using a Matrox frame grabber and Metamorph software (Universal Imaging, W. Chester, PA).

2.8 *In situ* DNA End Labeling of Oligodendrocytic Cells

The ApopTag™ method utilizes an ApopTag™ *in situ* apoptosis detection kit (Oncor, MD, USA), which detects nuclei with, cut 3'- OH ends of DNA. Oligodendrocytes at 16 DIV were treated with BM, BM-D9, IM and IM-D9 for 6, 12, 15, 18 and 24 h. Cells were fixed in 2% paraformaldehyde, followed by three washes in 0.1M PBS and permeabilization with 0.05% Tween-20 in PBS for 10 min at room temperature. Endogenous peroxidase was quenched with 1% H₂O₂ in PBS for 5 min at room temperature. Coverslips were then covered with 1X equilibration buffer for 30 min at room temperature and then incubated with terminal deoxynucleotidyl transferase (TdT) / reaction buffer (76 µl of reaction buffer + 32 µl of TdT enzyme) for 1h at 37°C. A stop wash buffer incubation for 30 min at 37°C was used to terminate the 3'-OH DNA extension reaction. After a PBS wash, the coverslips were incubated with antidigoxigenin peroxidase antibody. After three washes with 0.1M PBS, chromogenic detection was carried out using DAB (1.5 mg / ml) mixed with hydrogen peroxide (H₂O₂; 0.02% v/v) yielding a brown reaction product. Coverslips were dehydrated in ascending grade alcohol series, cleared with xylene and mounted on slides using a drop of permount. ApopTag™ positive nuclei were randomly counted in triplicate (described in

section 2.5), for each of the time points, for experimental series- I and II.

2.9 Determination As To Whether (-) -Deprenyl Or Its Metabolites Are Responsible For Oligodendrocyte Anti-Apoptosis

The capacity of the three major metabolites of (-) -deprenyl, namely, (-) -desmethyldeprenyl, (-) -amphetamine and (-) -methamphetamine (Heinonen *et al.*, 1994) to reduce the death of the oligodendroglial cells was assayed using the nuclear integrity assay. Three different general cytochrome P450 blockers - proadifen (Sigma), piperonyl butoxide; Aldrich Chem Co., WI) and 2-methyl-1,2-di(3-pyridyl)-1-propanone (metapyrone; Aldrich) were used to block the cytochrome P450 dependent metabolism of (-) -deprenyl to (-) -desmethyldeprenyl as a means of determining whether a metabolite, rather than (-) -deprenyl was responsible for any changes in survival.

OLs at 16 DIV were exposed to the different drug treatment conditions for 24 h, following which, the nuclear integrity assay was performed. On the day of the treatment, the cells growing in Nunc 24 well plates were washed twice with base media. Each treatment well received 50 μ l of the appropriate drug solution and the total volume in the well was made up to 500 μ l with either BM or IM.

Nuclear counts were obtained from quadruplicate wells per treatment condition and the experiment was repeated twice. OLs were exposed to the following treatment conditions: 1) IM, 2) BM, 3) BM-D9, 4) (-) -Desmethyldeprenyl (BM-Ds9), 5) IM-D9 and 6) IM + 10⁻⁹ M (-) -Desmethyldeprenyl (IM-Ds9).

The treatment conditions with the three general cytochrome P450 blockers were:

1) BM + Proadifen (2.5, 10, 25 μ M), 2) BM-D9 + Proadifen (2.5, 10, 25 μ M), 3) BM-Ds9 + Proadifen (2.5, 10, 25 μ M), 4) BM + Metapyrone (50 μ M), 5) BM-D9 + Metapyrone (50 μ M), 6) BM-Ds9 + Metapyrone (50 μ M), 7) BM + Piperonyl butoxide (100 μ M), 5) BM-D9 + Piperonyl butoxide (100 μ M), 6) BM-Ds9 + Piperonyl butoxide (100 μ M).

The effects of the other two metabolites of (-)-deprenyl, namely, (-)-methamphetamine and (-)-amphetamine on oligodendroglial cell survival were also tested. (-)-Methamphetamine was used at three doses (10^{-5} M, 10^{-7} M, 10^{-9} M) in combination with 10^{-9} M (-)-deprenyl while a single dose of 10^{-5} M (-)-methamphetamine was used with 10^{-9} M (-)-desmethyldeprenyl.

(-)-Amphetamine was used in four concentrations (10^{-3} M, 10^{-5} M, 10^{-7} M, 10^{-9} M) with (-)-deprenyl (10^{-9} M) while a single concentration of 10^{-5} M (-)-amphetamine was used in combination with (-)-desmethyldeprenyl (10^{-9} M).

2.10 Determination of the Relationship between New Protein Synthesis and Apoptosis in Oligodendrocytes

After determining that the alterations in oligodendroglial apoptosis was in fact induced by (-)-desmethyldeprenyl, a principal metabolite of (-)-deprenyl, the next logical step was to determine whether (-)-desmethyldeprenyl exerted its effects by a transcriptional- or a translational-dependent mechanism.

OLs at 16 DIV were washed twice with base media and exposed either to actinomycin, a transcriptional blocker or cycloheximide, a translational blocker for 24 h.

Actinomycin was used at 1, 2.5 and 50 µg / ml and cycloheximide at 1, 5, 10 and 50 µg / ml. Actinomycin and cycloheximide were either used with base media alone or in combination with 10^{-9} M (-) -desmethyldepronyl. Each treatment well received 50µl of the drug solution and the total volume of the well was made up to 500µl with base media.

Counts of intact nuclei, obtained from quadruplicate wells per treatment condition were used to quantitate the effects of the transcriptional and translational blockers. Each experiment was repeated twice for experimental density series-II.

2.11 Analysis of Changes in PROL and OL Protein Levels

2.11.1 Protein Extraction

O-2A progenitor cells were plated at a density of 1×10^6 / 100 mm petridishes. The progenitor cells were allowed to differentiate into PROLs and OLs in the presence of insulin and IGF-I. At 16 DIV, cultures were exposed to BM, IM, BM-D9 or BM-Ds9 for 24 h. Subsequently, cells were washed twice with 0.1M PBS, pH 7.4 and harvested with a Falcon cell scraper. After centrifugation at 2000 x g for 5 min in a Mistral 2000 centrifuge, the cells were incubated in 100µl of cell lysis buffer (25 mM Tris, pH 8.0, 0.5% Triton-X-100, 1mM EDTA, 10mM PMSF, 5mM Benzamidine, 5µM leupeptin). The lysate was homogenized with a plastic homogenizer. The lysate was centrifuged at 2000 x g for 5 minutes at 4°C. The supernatant containing the protein fraction was collected. A small volume of the protein solution was used to estimate the protein concentration. The rest of the protein solution was stored at -20°C until use.

2.11.2 Estimation of Protein Concentration

Total protein of the aliquot was determined by spectrophotometry based on the Bradford dye binding procedure (Bradford, 1976) using Coomassie Brilliant Blue (Pierce, Rockford, IL). Coomassie Brilliant Blue dye binds primarily to basic or aromatic residues on proteins and in the presence of the protein converts from cationic (red) to the anionic (blue) form by successive protonations. This conversion was quantitated by a Hitachi spectrophotometer at a wavelength of 595 nm. The assay was carried out by measuring the binding of the dye to the unknown protein. The protein - dye binding was then compared to different amounts of a standard protein, bovine serum albumin (BSA). Proteins with a molecular weight greater than 3 - 5 kDa are sensitively quantitated by the Bradford protein assay.

2.11.3 SDS - PAGE Electrophoresis

The protein samples obtained from the cultures after a 24-hour treatment period were separated by sodium dodecyl sulfate - polyacrylamide gel electrophoresis (SDS-PAGE) in duplicate. The SDS-PAGE electrophoresis separates proteins based on molecular size as they move through the polyacrylamide gel matrix from the cathode towards anode. The percentage of acrylamide in the separating gel depends on the molecular size of the protein electrophoresed. Proteins smaller than 50 kDa like MBP and PLP were resolved on a 10% SDS-PAGE discontinuous gel while proteins larger than 50 kDa like GC and CNPase-I were separated on a 15% SDS-PAGE discontinuous gel.

A 30% stock acrylamide solution was made up. A separating and stacking gel

mix was prepared using stock acrylamide, water, separating or stacking gel buffer, N,N,N',N'-tetramethyl ethylenediamine (TEMED) and ammonium persulfate (APS). APS was always made fresh for each experiment. The glass plate sandwich with spacers was assembled and placed in a Bio Rad Mini Protean II gel apparatus. Using Pasteur pipets, the separating gel was poured and the top of the gel was covered with a layer of isobutyl alcohol. The separating gel was allowed to polymerize for 1h at room temperature. The overlaid isobutyl alcohol on the separating gel was poured out and the stacking gel was poured. Subsequently, a 10 well Teflon comb was placed in the stacking gel and the gel was allowed to polymerize. The protein samples were solubilized in sample buffer (glycerol, Tris, pH 6.8, 0.01% Bromphenol blue, 20 mM Dithiothreitol, SDS) in a 1:1 ratio, sample to buffer. The protein samples in tubes were transferred to a 100°C water bath for 5 minutes to inactivate proteases. The samples were then loaded carefully as a thin layer on the bottom of the polymerized wells. An electrophoresis buffer (Glycine, Tris, pH 8.3, SDS) was used to fill up the upper and lower buffer chambers. A Bio-Rad model 250 / 2.5 power supply was used to resolve the samples at 70 volts through the stacking gel and at 100 volts through the separating phase of the gel.

2.11.4 Detection of Proteins By Western Blotting Immunodetection method

The oligodendroglial proteins separated by SDS-PAGE were transferred to Hybond-C nitrocellulose membrane (Amersham Life Science) which is optimized for protein transfer, using a Bio-Rad Mini Protean II transfer apparatus. All the filter papers and nitrocellulose membranes were first equilibrated in a transfer buffer (Glycine, Tris, SDS, 20% Methanol). The transfer apparatus was connected to a power supply and the

protein transfer was carried out at 100 mA for 3 h. After the transfer period, the membrane was removed and proteins were visualized by staining for 5 min with Ponceau S stain (0.5% Ponceau S and 1% acetic acid). Ponceau S staining is primarily used to verify transfer efficiency. The membrane was destained with distilled water.

Prior to immunodetection, non-specific binding sites on the membrane were blocked by immersing it in a blocking buffer (5% Carnation nonfat dry milk in 0.1M PBS) for an hour at room temperature with shaking. The membrane was rinsed with 0.1M PBS twice and incubated in a primary antibody overnight at 4°C. The primary antibodies used were diluted in 1% nonfat dry milk in PBS. The following monoclonal primary antibodies were used: rat anti-MBP (82-87 amino acid region) (1:400; Serotec Ltd., UK), rat anti-PLP (1:200; Immuno Diagnostics, Inc., MA), mouse anti-CNPase (1:500; Sternberger Monoclonals Inc., MD) and rabbit anti GC (1:250; Sigma). Following overnight incubation in primary antibodies, the membranes were washed four times with a wash buffer consisting of Tris Buffered Saline (TBS) containing 0.1% Tween-20. The blot was incubated in rat, rabbit or mouse IgG-horseradish peroxidase-conjugated secondary antibody for an hour at room temperature. The secondary antibody was used at a dilution of 1:500 in 1% nonfat dry milk. The blots were washed five times with TBS containing 0.1% Tween-20.

To visualize the antigen-antibody interaction in the immunoblots, an enhanced chemiluminescent method (ECL) was used. The horseradish peroxidase labeled ECL reaction involves a substrate solution containing luminol. Oxidized luminol substrate gives off a blue light that can be trapped on a film. For the ECL reaction, a Supersignal™ Substrate (Pierce, Rockford, IL) working solution containing luminol / enhancer solution

and a stable peroxide solution in a 1:1 v / v ratio was used. The blots were placed in the Supersignal™ Substrate working solution for 5 minutes at room temperature with shaking. A sufficient amount of the solution was used to ensure that the blot remained completely wetted. After five minutes, the blot was removed from the Supersignal™ Substrate working solution and placed in a plastic wrap. Any excess of the working solution or bubbles between the blot and the plastic wrap was removed. The blots were placed against a Kodak Biomax-MR double emulsion film in an autoradiographic cassette. Typically, blots were exposed to the films for 1-10 seconds and the films were developed.

2.12 Assessment of Mitochondrial Membrane Potential in Oligodendroglial Cells

2.12.1 CMTMR Estimation of Mitochondrial Membrane Potential

The $\Delta\Psi_M$ was assessed by the addition of a lipophilic, potentiometric dye, chloromethyl-tetramethylrhodamine methyl ester (CMTMR, Mitotracker Orange™ - Molecular Probes, Eugene, OR). The CMTMR dye reacts with the thiol groups on proteins and peptides to form aldehyde fixable conjugates. Entry of the negatively charged mitochondrial matrix compartment is proportional to the difference in the membrane potential. Therefore, the CMTMR fluorescence labels the mitochondrial membrane potential generated due to the negativity difference between the mitochondrial matrix and the outside of the mitochondria. Upon cell fixation, CMTMR remains in the mitochondria and is not washed out unlike other mitochondrial potentiometric dyes like rhodamine123.

Oligodendrocytes at 16 DIV were placed in trophically deprived BM for 18h or

treated with BM-D9 or BM-Ds9. Other treatments of cultures included exposure to the general cytochrome P450 blockers as well as the metabolites of (-)-deprenyl as previously described in section 2.8 of this thesis. At 18h after trophic withdrawal or drug treatments, the media in each well was replaced with similar media containing 138 nM CMTMR. The cells were incubated in CMTMR at 37°C for 15 min. The cells were then fixed with 4% cold paraformaldehyde on ice for 30 min and washed twice with 0.1M PBS. Consequently, the coverslips were mounted on glass slides with Aquamount (Gurr, England).

2.12.2 Confocal Microscopy

Individual mitochondria labeled with CMTMR were resolved by confocal microscopy. A Leica true confocal scanning (TCS) 4D microscope coupled to an argon-krypton laser (Omnichrome, USA) was used for cell imaging. A pinhole size of 20 with an excitation filter wavelength of 568 nm and an emission filter wavelength of 590 nm was used to image the CMTMR labeled mitochondria. Each field of the coverslip was imaged using an oil-immersion, 100X, 1.3 N.A. objective at 512 by 512 by 8 bits per pixel resolution, background offset of -1 and line averaged 32 times in bi-directional line scan mode. Care was taken not to exceed the dynamic range of the gray value display. The confocal images obtained were saved on an optical drive in a tagged image file format (TIFF).

2.12.3 Measurement of CMTMR Fluorescence Intensity

Fluorescence intensity of individual mitochondria was measured using the

Metamorph™ program. Metamorph™ compiles measurements of objects in a 8-bit image ranging from gray values 0 (background) and 255. In order to obtain fluorescence intensity measures, a rectangular region tool of 2x2 pixels was used to measure two randomly selected areas within each mitochondrion. A total of ten mitochondria obtained equally from all the regions of each cell were measured within each image. About 20 images were analyzed for each treatment condition thereby giving a sum of about 400 mitochondrial fluorescence intensity measures. The raw values were then further graphed and analyzed with the Microcal Origin 4.1 program. Frequency count was performed on the data, which classified the data in ordered bins. A frequency distribution was obtained with lower bin value set at 0 and higher bin value set at 260.

2.13 Statistical Analysis

In order to statistically evaluate the data, the individual measurements of data from different treatment groups were first analyzed using Statistica™ software (StatSoft) to carry out two-tailed independent sample t-testing. Analysis with parametric methods such as the t-test may not provide valid results, especially with small n numbers. The data was therefore rank ordered and compared in a pairwise fashion using Statistica™ software to perform non-parametric Mann Whitney U testing (Siegel, 1956). Both methods depend on permutational mathematics to calculate significance values and therefore do not require homogeneity of variances, that the underlying distributions for the data be known, or that the values are linearly related.

3.0 Results

3.1 Differentiation and Maturation of O-2A Progenitors

Phase contrast microscopy revealed cells with a round cell body of about 10 μm in diameter with a round nucleus and two long thin bipolar processes extending from the cell body at about an angle of 180 degrees to each other. Those cells were found to be immunopositive for an A2B5 antibody which is characteristic of O-2A progenitor cells (Eisenbarth *et al.*, 1979). Figure 1A shows a phase contrast image of a typical O-2A progenitor, which is marked by the white arrow. The interference contrast image in figure 2A shows four cells with the bipolar morphology that are immunopositive for A2B5. Only cells with the bipolar morphology were found to be A2B5 immunopositive. On 12 DIV, 24 hours after the cultured cells were removed from the astrocyte feeder layer and replated on coverslips at 11 DIV, A2B5 immunopositive cells accounted for more than 75% of the cultured cells.

By 13 DIV, phase contrast microscopy revealed increasing numbers of cells with three to four processes emanating from the cell body. Figures 1B and 1C present phase contrast images of the cells. The white arrows in the figures mark typical examples. These cell bodies and processes of those cells were found to be immunoreactive for the antibodies CNPase-I and GC which have been shown to identify PROLs (Knapp, 1988; Ranscht, 1982). Cells with the multiple processes did not immunoreact for the A2B5 antibody or for antibodies to MBP. By 14 and 15 DIV, the PROLs constituted a major proportion of the cells in the cultures.

By 15 and 16 DIV, the PROLs elaborated more complex processes. These cells were highly branched and had 6 to 8 main processes. As shown by the typical cell marked by the white arrow in figure 1D, the interlacing small secondary and tertiary processes gave the processes a web-like appearance. Cells with the web-like processes were immunopositive for MBP (shown in figure 2D) and PLP (shown in figure 2E). MBP (Lees, 1984) and PLP (Bartlett *et al.*, 1988) have been shown to be markers for OLs. The MBP expression could be seen in the oligodendroglial processes as well as in the cell body. An intense staining of PLP was found in the cell body. Some of the MBP positive cells were also found to have flat MBP positive membranes attached to the web-like processes.

A small proportion of cells displayed a flattened morphology with a large round nucleus. These cells immunoreacted to the antibody glial fibrillary acidic protein (GFAP) as shown in figure 2F. The cells also possessed GFAP positive reticulated somal areas. These observations led to the identification of the GFAP positive cells as ASTs (Raff *et al.*, 1979). Less than 1% of the cells in culture showed a non-process bearing amoeboid morphology and were identified as microglia.

Typically, 16 DIV culture comprised of 4% AST, 2% O-2A, 32% PROL and 62% OL (see figure 5 below). Since the differentiated PROL and OLs accounted for more than 93% of the total cells at 16 DIV, all the experiments reported in this thesis used 16 DIV cultures. The progressive increase in OLs and PROLs and the progressive decrease in O-2As between DIV 12 and 16 and the small numbers of ASTs at 16 DIV showed that the base media, with IGF-I and insulin added, favored the differentiation of O-2As along the oligodendrocyte pathway rather than along the type 2 astrocyte pathway. The methods reliably provided large number of identifiable PROLs and OLs at 16 DIV. The studies of apoptosis were therefore carried out at 16 DIV.

3.2 Decreased Survival of Oligodendroglial Cells after Insulin and IGF-I

Withdrawal

Cultures on 16 DIV were washed free of serum, insulin and IGF-I. The wash media was then replaced with BM. Control cultures were placed in IM. The washing and replacement with defined media served to suddenly withdraw IGF-I and insulin from the cells. The cells were exposed to either BM or IM for a 24 h period after which cell survival was estimated using counts of intact nuclei. Two independent series of experiment were carried out at different plating densities.

3.2.1 Counts Of Intact Nuclei

IGF-I and insulin withdrawal resulted in a decrease in numbers of intact nuclei at 24h after washing. In experimental series-I (plating density of 5.3×10^3 cell/mm²), counts of intact nuclei decreased to 54.8% (bar labeled BM in figure 3A1) compared to the

intact nuclear counts for cells that were washed and replaced in media with IGF-I and insulin (bar labeled IM in figure 3A1). A similar decrease to 51.4% was observed in experimental series-II (plating density of 15.8×10^3 cell/mm²) as shown by the bars labeled IM and BM in figures 3A2. Table I presents the statistical probabilities for experimental series I and II. Each experimental series for the total intact cell counts consisted of three or four independent experiments.

Experiments were carried out to determine whether (-) -deprenyl altered the reduction in the counts of intact nuclei induced by IGF-I and insulin withdrawal. After washing and placement in insulin and IGF-I free media supplemented with 10^{-9} M (-) -deprenyl (bars labeled BM-D9 in figure 3A1), the numbers of intact nuclei were 119% of those in IM in experimental series- I so that (-) -deprenyl increased the number of cells after IGF-I and insulin withdrawal by 217% (compare bars labeled BM-D9 and BM in figure 3A1). The BM decrease to 84.45% of IM was smaller in experimental series- II but BM-D9 still showed an increase of 164% compared to BM (compare BM and BM-D9 bars in figure 3A2). When cells were placed in IM with 10^{-9} M (-) -deprenyl (IM-D9 bars), the number of intact nuclei were 135.6% compared to IM in experimental series- I and 102.4% compared to IM for experimental series- II (figure 3A2).

According to the counts of intact nuclei, treatment with 10^{-9} M (-) -deprenyl induced a significant increase in numbers of intact nuclei both for cells washed and replaced in media with IM and those washed and placed in BM (see table 1).

Table 1. Statistical testing of data for intact nuclear and cell counts

| Experimental Series - I | | Experimental series - II | |
|---------------------------------|-----------------------|---------------------------------|-----------------------|
| T- test for independent samples | | T- test for independent samples | |
| Treatment | Intact nuclear counts | Treatment | Intact nuclear counts |
| IM-D9 / IM | 1.9×10^{-5} | IM-D9 / IM | 5.3×10^1 |
| BM / IM | 1.1×10^{-13} | BM / IM | 1.2×10^7 |
| BM-D9 / IM | 2.8×10^{-4} | BM-D9 / IM | 9.9×10^5 |
| BM-D9 / BM | 1.4×10^{-13} | BM-D9 / BM | 4.7×10^7 |

| Mann - Whitney U test | | Mann - Whitney U test | |
|-----------------------|-----------------------|-----------------------|-----------------------|
| Treatment | Intact nuclear counts | Treatment | Intact nuclear counts |
| IM-D9 / IM | 1.1×10^5 | IM-D9 / IM | 3.9×10^1 |
| BM / IM | 1.3×10^{-8} | BM / IM | 6.6×10^4 |
| BM-D9 / IM | 7.1×10^5 | BM-D9 / IM | 1.3×10^3 |
| BM-D9 / BM | 1.3×10^8 | BM-D9 / BM | 1.6×10^4 |

The increase in numbers of intact nuclei for cells that were washed and replaced in media with IM was compatible with two interpretations: 1) that (-)-deprenyl induced the increased number of intact nuclei in cells that were washed and placed in media BM by increasing the replication rates of the cells, and 2) that (-)-deprenyl decreased the death of the cells caused by IGF-I and insulin withdrawal and also decreased a baseline death process that was present in cells washed and replaced in IM.

3.2.2 Total Counts of Methylene Blue Stained Cells

The counting of methylene blue stained cells plated on coverslips resulted in data, which paralleled that found for counts of intact nuclei above. In experimental series-I, washing and placement of cells in BM (bar labeled BM in figure 3B1) decreased in the intact cell counts of 16.2% with respect to cells that were washed and replaced in media IM (bar labeled IM in figure 3B1). Similarly, the BM intact cell counts decreased to 39.4% of IM in experimental series-II (figure 3B2). Similar to the intact cell counts, treatment with (-)-deprenyl (BM-D9) increased the number of intact methylene blue stained cells to 576% of those in BM in experimental series- I (figure 3B1) and 255 % of those in BM in experimental series- II (figure 3A2).

The number of intact methylene blue stained cells in IM-D9 were 128.9% (experimental series- I) and 130.6% (experimental series- II) relative to IM (figures 3B1, and 3B2). The data obtained from the intact nuclear counts and cell counts showed that (-)-deprenyl increased the numbers of oligodendroglial cells when administered in combination with either BM or IM. Like the data for counts of intact nuclei, the changes induced by (-)-deprenyl could result from an increase in replication or a decrease in cell

death.

3.2.3 Intact Cell Counts for Individual Cell Types in Cultures

The characteristic morphologies for the O-2A, PROL, OL and AST cells as revealed by immunocytochemical identification above allowed the identification of the cell types on methylene blue stained coverslips. Figure 4A-D shows typical methylene blue stained O-2A, PROL, OL and AST cell types.

On washing and placement in BM, the counts of all four cell types showed a significant reduction in numbers (see figure 5). In experimental series-I, the numbers for BM, when compared to IM, were 30.3%, 69.2%, 14.0%, 15.1% for ASTs, O-2As, PROLs and OLs respectively (figure 5A). As above for the total cell counts, relatively less cell death was observed in experimental series-II. The survival in BM compared to IM for experimental series-II was 71.2%, 42.2%, 37.3%, 35.0% for ASTs, O-2As, PROLs and OLs respectively (figure 5B). Note that among the four cell populations, maximum decreases in numbers were seen in the more differentiated PROL and OL cells.

(-) -Deprenyl increased the numbers of all the four types of cells in the IGF-I and insulin withdrawn cultures. For BM-D9, cell numbers increased compared to those in BM to 570% for ASTs, 244% for O-2As, 739.2% for PROLs and a 565.0% for OLs in experimental series-I (figure 5A) and to 132% for ASTs, 176% for O-2As, 275% for PROLs and 291% for OLs for experimental series II (figure 5B).

Table 2. Statistical testing of data for counts of individual cell types

| Experimental Series - I | | | | | | Experimental Series - II | | | | | |
|----------------------------------|----------------------|----------------------|----------------------|-----------------------|------------|----------------------------------|----------------------|-----------------------|-----------------------|--|--|
| T - test for independent samples | | | | | | T - test for independent samples | | | | | |
| Treatment | AST | O-2A | PROL | OL | Treatment | AST | O-2A | PROL | OL | | |
| IM-D9 / IM | 4.2×10^{-3} | 1.1×10^{-2} | 7.2×10^{-4} | 9.5×10^{-1} | IM-D9 / IM | 2.1×10^{-4} | 1.0×10^{-2} | 5.9×10^{-2} | 1.1×10^{-3} | | |
| BM / IM | 8.9×10^{-3} | 5.0×10^{-1} | 1.0×10^{-6} | 6.0×10^{-9} | BM / IM | 1.5×10^{-4} | 2.7×10^{-4} | 3.2×10^{-1} | 1.3×10^{-12} | | |
| BM-D9 / IM | 5.8×10^{-2} | 2.3×10^{-1} | 8.6×10^{-1} | 3.1×10^{-1} | BM-D9 / IM | 4.5×10^{-1} | 1.2×10^{-1} | 8.1×10^{-1} | 8.6×10^{-1} | | |
| BM-D9 / BM | 7.0×10^{-6} | 5.4×10^{-2} | 2.7×10^{-9} | 3.0×10^{-12} | BM-D9 / BM | 1.6×10^{-3} | 1.3×10^{-2} | 1.3×10^{-12} | 1.1×10^{-12} | | |
| Mann - Whitney U Test | | | | | | Mann - Whitney U Test | | | | | |
| Treatment | AST | O-2A | PROL | OL | Treatment | AST | O-2A | PROL | OL | | |
| IM-D9 / IM | 2.7×10^{-2} | 8.6×10^{-2} | 1.3×10^{-3} | 6.5×10^{-1} | IM-D9 / IM | 5.5×10^{-5} | 2.4×10^{-2} | 3.3×10^{-2} | 3.5×10^{-3} | | |
| BM / IM | 1.0×10^{-1} | 9.3×10^{-1} | 5.7×10^{-4} | 4.8×10^{-7} | BM / IM | 3.6×10^{-4} | 5.9×10^{-3} | 4.2×10^{-1} | 2.1×10^{-11} | | |
| BM-D9 / IM | 4.5×10^{-2} | 3.1×10^{-1} | 5.3×10^{-1} | 6.7×10^{-1} | BM-D9 / IM | 4.5×10^{-1} | 3.1×10^{-1} | 8.1×10^{-1} | 9.6×10^{-1} | | |
| BM-D9 / BM | 1.0×10^{-4} | 2.5×10^{-1} | 9.7×10^{-8} | 9.5×10^{-9} | BM-D9 / BM | 3.1×10^{-3} | 6.5×10^{-2} | 4.0×10^{-11} | 6.7×10^{-10} | | |

For IM-D9, the numbers of cells relative to those for IM were 227% for AST, 315% for O-2As, 196% for PROLs and 99% for OLs for experimental series -I (figure 6A). In experimental series - II, IM-D9 cell numbers relative to IM were 132% for AS, 160% for O-2As, 120% for PROLs and 140% for OLs for experimental series -II (figure 5B). Table 2 summarizes the statistical probabilities.

3.3 Oligodendroglial Cell Death on Withdrawal of Insulin and IGF-I

3.3.1 Morphological Changes

After washing and placement in BM, the web-like processes of OLs underwent fragmentation. Figure 6 show typical transmission (A1 and B1) interference contrast images (A2 and B2) of OLs at 18h after washing that were immunoreacted for MBP. A1 and A2 are for cells that were washed and replaced in IM while B1 and B2 are for cells that were washed and placed in media only. B1 and B2 show the fragmentation of the OL processes with relative maintenance of cell body structure. The process fragmentation was noted increasing after 6h following IGF-I and insulin withdrawal.

3.3.2 Evidence For Apoptotic Degradation after IGF-I and Insulin Withdrawal

Electrophoresis gels for DNA extracted from the cells at 18h after washing on 16 DIV showed DNA ladders with a period of about 180 bp for BM while electrophoresis for IM and BM-D9 did not show detectable laddering (figure 7A).

Staining of the oligodendroglial cells with a supravital, bisbenzimide dye, Hoechst 33258 revealed nuclear chromatin condensation and typical apoptotic bodies (see fluorescence images in figure 7D1 and 7D2 for BM at 18 hours after washing, apoptotic bodies and condensed DNA are marked by open arrows while normally staining nuclei are marked by the white arrows). The Hoechst 33258 staining was identical to that which our laboratory found in neuronally differentiated PC12 cells after serum and NGF withdrawal (see (Wadia *et al.*, 1998)).

Similarly *in situ* end labeling (ISEL) using the ApopTag™ method revealed a proportion of nuclei in both BM and IM with evidence for DNA fragmentation as shown in the figure 7B and 7C (the images are for cells in BM at 18 hours after washing). Taken together the DNA ladders, chromatin staining and ISEL indicated that a significant proportion of the cells died by the process of apoptosis and the apoptosis was more evident after IGF-I and insulin withdrawal than it was for cells supported by IGF-I and insulin.

3.3.3 Time Course and Magnitude of Apoptotic Nuclear Changes

Counts of ApopTag™ positive nuclei were obtained for 5 of the time points after washing to determine the time course of the appearance of apoptotic nuclear degradation in the cultures. Significant numbers of ApopTag™ positive nuclei were found at all time points for cells in IM (2.3% and 3.4% of total intact cell counts / mm² for the two series respectively). This finding indicated a baseline level of apoptosis in the cultures supported by IGF-I and insulin. A significant level of baseline apoptosis has been found in most neural culture systems (see (Wadia *et al.*, 1998)). The baseline level therefore

must be taken into accord when judging the effect of agents that promote or reduce apoptosis. Addition of 10^{-9} M (-) -deprenyl to the IM did not significantly change the number of ApopTag™ positive nuclei at any time point in either experimental series.

Withdrawal of IGF-I and insulin induced a gradual but marked increase in the number of ApopTag™ nuclei that reached a maximum at 18 hours after washing. Comparison of the values at each time point for BM and IM shows that the withdrawal of IGF-I and insulin markedly increased the number of ApopTag™ nuclei above the baseline values found for IM. Addition of 10^{-9} M (-) -deprenyl to the base media, significantly decreased the numbers of ApopTag™ nuclei in both experimental series (see table 3 for statistical probabilities). These data clearly establish that the cultured oligodendroglial cells die by apoptosis after IGF-I and insulin withdrawal and that (-) - deprenyl significantly reduces that apoptosis. It establishes that the increase in numbers of intact nuclei and methylene blue stained cells resulted at least in part from an anti-apoptotic action of (-) -deprenyl.

Table 3. Statistical analysis of data for time course of apoptosis of oligodendroglial cells

| | | Experimental series - I | | | | | | Experimental series - II | | | | | |
|------------|----------------------|---------------------------------|-----------------------|-----------------------|----------------------|----------------------|----------------------|---------------------------------|----------------------|-----------------------|-----------------------|----------------------|-----|
| | | T- test for independent samples | | | | | | T- test for independent samples | | | | | |
| | | 6h | 12h | 15h | 18h | 24h | Treatment | 6h | 12h | 15h | 18h | 24h | |
| Treatment | IM-D9 / IM | 4.8×10^{-1} | 1.8×10^{-1} | 1.0 | 8.4×10^{-1} | 1.6×10^{-1} | IM-D9 / IM | 3.5×10^{-1} | 7.7×10^{-1} | 7.8×10^{-2} | 2.0×10^{-1} | 7.4×10^{-1} | |
| BM / IM | 1.9×10^{-7} | 2.2×10^{-4} | 1.0×10^{-13} | 1.3×10^{-8} | 1.2×10^{-5} | BM / IM | 1.5×10^{-9} | 1.7×10^{-5} | 4.5×10^{-8} | 7.5×10^{-10} | 3.8×10^{-12} | | |
| BM-D9 / IM | 2.5×10^{-4} | 5×10^{-6} | 2.3×10^{-1} | 1.3×10^{-4} | 9.0×10^{-4} | $BM-D9 / IM$ | 2.2×10^{-2} | 1.8×10^{-3} | 3.6×10^{-2} | 3.7×10^{-8} | 2.0×10^{-4} | | |
| BM-D9 / BM | 8.4×10^{-4} | 3.8×10^{-1} | 1.7×10^{-12} | 3.5×10^{-5} | 5×10^{-6} | $BM-D9 / BM$ | 2.0×10^{-6} | 3.6×10^{-2} | 3.4×10^{-5} | 2.4×10^{-8} | 3.2×10^{-7} | | |
| | | Mann - Whitney U Test | | | | | | Mann - Whitney U Test | | | | | |
| Treatment | IM-D9 / IM | 7.9×10^{-1} | 4.9×10^{-1} | $12h$ | $15h$ | $18h$ | 24h | Treatment | 6h | 12h | 15h | 18h | 24h |
| BM / IM | 4.6×10^{-5} | 1.3×10^{-2} | 6.2×10^{-13} | 9.9×10^{-1} | 3.9×10^{-1} | $IM-D9 / IM$ | 3.4×10^{-1} | 2.3×10^{-1} | 8.3×10^{-1} | 5.4×10^{-1} | 7.9×10^{-1} | | |
| BM-D9 / IM | 1.1×10^{-3} | 2.0×10^{-5} | 4.3×10^{-1} | 2.2×10^{-10} | 1.2×10^{-5} | BM / IM | 5.9×10^{-8} | 3.0×10^{-3} | 4.0×10^{-6} | 2.1×10^{-10} | 7.2×10^{-9} | | |
| BM-D9 / BM | 1.3×10^{-2} | 7.8×10^{-1} | 7.9×10^{-12} | 1.0×10^{-5} | 7.3×10^{-4} | $BM-D9 / BM$ | 5.3×10^{-5} | 8.2×10^{-2} | 4.4×10^{-4} | 2.9×10^{-5} | 7.1×10^{-5} | | |

3.4 (-)-Deprenyl But Not (+)-Deprenyl Increases Oligodendroglial Survival

Studies in neuronally differentiated PC12 cells after serum and NGF withdrawal

(Tatton *et al.*, 1994) and immature facial neurons after axotomy (Ansari *et al.*, 1993)

showed that (-)-deprenyl decreased the apoptotic death of the cells while (+)-deprenyl did not have any effect on the survival of the cells. I examined the relative effects of the two enantiomers on oligodendroglial survival after IGF/insulin withdrawal at three different concentrations (see figure 9). The (-)-enantiomer induced a graded increase in the numbers of intact nuclei with the greatest increase for 10^{-9} M. The gradual decrease in cell numbers with increasing concentration from 10^{-9} to 10^{-5} M is similar to that found for neuronally differentiated PC12 cells after serum and NGF withdrawal (Tatton *et al.*, 1994). In that model, (-)-deprenyl was also most effective in reducing apoptosis at 10^{-9} M.

In the oligodendroglial cells, the (+)-enantiomer did not alter the numbers of intact nuclei from the values found for BM for any of the three concentrations tested. Accordingly, these results indicate that the anti-apoptotic action of (-)-deprenyl on the oligodendroglial cells is stereospecific.

3.5 Alterations in the Levels of Proligodendrocyte and Oligodendrocyte Specific Marker Proteins

To determine the changes in the levels of proteins specific to the PROLs and the OLs, Western blots were performed for protein extracts from cultures washed and placed in BM/IM/BM-D9/BM-Ds9/IM-D9 for 18 hours. Anti-MBP (OL marker), anti-PLP (OL marker), anti-GC (PROL marker) and anti-CNP (PROL marker) antibodies were used to determine the levels of the OL and PROL marker proteins.

The anti-MBP antibody recognized two distinct isoforms of myelin basic protein at 21 and 14 kDa. As shown in the Western blot labeled myelin basic protein in figure 10, the immunodensity of the 21 and 14 kDa bands for the BM sample were reduced compared to the IM sample indicating that withdrawal resulted in a decrease in the level of MBP. Since an equal amount of total protein was loaded into each of the lanes, the decrease indicates a decreased proportion of MBP in the sample. The decrease could result from a net decrease in OLs relative to other cell types in samples which would correspond, at least in part, to the greater proportional loss of PROLs and OLs than O2-A cells and AST cells shown above. It could also result from an induction of decreased expression of the MBP gene in response to IGF-I and insulin withdrawal.

Probing of the blots for the second OL protein marker, PLP, revealed a visible 25 kDa band together with a faintly visible 30 kDa (Western blot labeled Proteolipid protein in figure 10). As in this example, there was no apparent change in the immunodensity for the anti-PLP antibody when the BM and IM samples were compared. A decrease in band density might be expected given the count data above that revealed a proportionally greater loss of PROLs than O-2As and ASTs. A decrease in band density due to

decreased numbers of PROLs containing PLP may have been offset by an overall increase in PLP expression at the time of the samples.

Similar to MBP, both GC (see the distinct 60 kDa single band in the Western blot in figure 10 labeled galactocerebroside) and CNPase-I (see the distinct 45 kDa single bands in the Western blot in figure 9 labeled cyclic nucleotide phosphorylase) showed a decrease in immunodensity for BM compared to IM which indicates an effect of IGF-I and insulin withdrawal on PROLs.

The dramatic findings on the western blots were provided by the treatment of the IGF-I/insulin withdrawn cells with 10^{-9} M (-)-deprenyl (lanes labeled BMD9) and 10^{-9} M (-)-desmethyldeprenyl, the major metabolite of (-)-deprenyl (lanes labeled BMDS9). For each of the marker proteins, including PLP, which did not show a decrease after IGF-I/insulin withdrawal, treatment with either of the compounds resulted in a marked increase in immunodensity compared to BM. The increases are in keeping the increased survival of the PROLs and OLs induced by (-)-deprenyl and (-)-desmethyldeprenyl (see below). For MBP, CNP-ase I and PLP, the band densities for BMD9 or BMDS9 exceed those for IM, suggesting that (-)-deprenyl and (-)-desmethyldeprenyl induced an increase in expression of the genes for the proteins.

3.6 (-)-Desmethyldeprenyl, An Active Metabolite of (-)-Deprenyl Is Responsible For the Reduction in Oligodendroglial Apoptosis

(-) -Deprenyl on oral administration is rapidly metabolized in the liver and the gastrointestinal tract by cytochrome P450 enzymes to three principal metabolites, (-) -desmethyldeprenyl, (-) -methamphetamine and (-) -amphetamine (Heinonen *et al.*, 1994; Rohatagi *et al.*, 1997a; Rohatagi *et al.*, 1997b). Experiments were carried out to determine the effects of the principal metabolites of (-) -deprenyl on oligodendroglial survival.

Withdrawal of insulin and IGF-I for 24 hours led to intact nuclear counts in BM decreasing to 48.7% compared to those replaced into IM (compare white bars in the groups of bars labeled IM and BM in figure 11). As shown in the experiments presented above, washing and placement of the cells in media without IGF-I and insulin, addition of 10^{-9} M (-)-deprenyl increased the counts of intact nuclei by 194 % compared to those for BM (compare the white and black bars in the BM group of figure 11). Treatment of cultures with 10^{-9} M (-)-desmethyldeprenyl induced an almost identical 197% increase in the counts (compare the white and gray bars in the BM group of figure 11). Controls of adding (-)-deprenyl or (-)-desmethyldeprenyl to cells supported by IGF-I and insulin resulted in the numbers of intact nuclei that were 107% and 103% relative to IM (group labeled IM in figure 11).

In contrast to (-)-desmethyldeprenyl, (-)-methamphetamine (MA) or (-)-amphetamine (AM) did alter the counts of intact nuclei. Each was tested at three concentrations of 10^{-5} , 10^{-7} and 10^{-9} M (compare white bars in the groups labeled BM+MA and BM+AM to the white bar in the BM group of figure 11). The statistical

probabilities are shown in Table 5. This data suggests that (-)-desmethyldeprenyl but not (-)-methamphetamine or (-)-amphetamine may mediate the anti-apoptotic actions of (-)-deprenyl on the oligodendroglial cells. It has previously been shown that (-)-desmethyldeprenyl and (-)-desmethyldeprenyl are similarly effective in reducing apoptosis in primary cultures of rat dopaminergic cells after exposure to excitotoxicity (Mytilineou *et al.*, 1997) but it is not known whether one or both of the agents mediate the anti-apoptotic effect. I used blockade of P450 enzyme metabolism of (-)-deprenyl to determine whether one or both mediated the anti-apoptosis..

Three general inhibitors of P450 enzymes, proadifen, metapyrone and piperonyl butoxide, were used to block the P450 enzyme dependent metabolism of (-)-deprenyl into its metabolites. Addition of proadifen at 2.5, 10 and 25 μ M with 10⁻⁹ M (-)-deprenyl resulted in a decrease in the number of intact nuclei to 144%, 109% and 91% when compared to IM (compare the black bars in the groups labeled BM+ Proad to that in the BM group in figure 11). Importantly, the three concentrations of proadifen did alter the values for BM only (compare the white bars in the groups labeled BM+ Proad to that in the BM group in figure 11). Furthermore, the three concentrations of proadifen did not reduce the increase in intact nuclei induced by 10⁻⁹ M (-)-desmethyldeprenyl (compare the gray bars in the groups labeled BM+ Proad to that in the BM group in figure 11). The two other cytochrome P450 enzyme blockers, metapyrone at 50 μ M and piperonyl butoxide at 100 μ M had similar actions to proadifen (groups labeled BM+ Meta and BM+P.But. in figure 11).

The statistical probabilities for these data are indicated in Table 4. The results obtained show that the general cytochrome P450 blockers completely eliminated the survival enhancing effect of (-)-deprenyl but did not alter the capacity of (-)-desmethyldeprenyl to increase the survival of oligodendroglial cells. Hence the anti-apoptotic effect of (-)-deprenyl on the oligodendroglial cells requires its metabolism to (-)-desmethyldeprenyl.

3.7 (-)-Methamphetamine and (-)-Amphetamine Competitively Reduce the Capacity of (-)-Desmethyldeprenyl to Reduce Oligodendroglial Apoptosis

Studies of facial motoneuron survival after axotomy in mice showed that treatment with (-)-methamphetamine and (-)-amphetamine reduced the effectiveness of (-)-deprenyl in improving the survival of the motoneurons (Oh *et al.*, 1994). The basis for the reduction in effectiveness is not known. I therefore undertook competition experiments to determine whether either of the metabolites reduced the capacity of (-)-deprenyl or (-)-desmethyldeprenyl to increase oligodendroglial survival after IGF-I and insulin withdrawal.

Methamphetamine when used in 10^{-5} M, 10^{-7} M and 10^{-9} M concentrations in combination with 10^{-9} M (-)-deprenyl significantly reduced the increase in numbers of intact nuclei induced by (-)-deprenyl in a graded concentration dependent manner (compare the black bars in the BM+MA group with the black bar in the BM group of figure 11) and 10^{-5} M (-)-methamphetamine had a similar competitive action on 10^{-9} M (-)-desmethyldeprenyl (compare the gray bar in the BM+MA group with the black bar in the BM group of figure 11).

Similarly (-)-amphetamine was used at 10^{-3} M, 10^{-5} M, 10^{-7} M and 10^{-9} M concentrations in combination with 10^{-9} M (-)-deprenyl or 10^{-9} M (-)-desmethyldeprenyl (compare the black and gray bars in the group labeled BM+AM with the black and gray bar in the BM group). Although, the addition of (-)-amphetamine markedly reduced the capacity of (-)-deprenyl to increase the survival of the oligodendroglial cells after IGF-I and insulin withdrawal , grading with concentration not as evident as with (-)-methamphetamine, in part due to greater sample to sample variation (see table 5 for statistical probabilities). (-)-Amphetamine at 10^{-5} M completely eliminated the capacity of 10^{-9} M (-)-desmethyldeprenyl to increase the survival of the oligodendroglial cells.

These data indicate suggest that the tissue levels of (-)-methamphetamine and/or (-)-amphetamine can be major factors in determining the effectiveness of (-)-deprenyl or (-)-desmethyldeprenyl in reducing oligodendroglial apoptosis. As shown above, the competition does not appear to reflect a pro-apoptotic effect of (-)-methamphetamine or (-)-amphetamine but rather seems to depend on an interference with the mechanism(s) underlying the anti-apoptosis by (-)-desmethyldeprenyl.

Table 4. Statistical analysis of data for intact nuclear counts after drug treatments

| Treatment | T-test for independent samples | | Mann-Whitney U test |
|---|--------------------------------|-------------------------|-----------------------|
| | Intact nuclear counts | Intact nuclear counts | Intact nuclear counts |
| BM / IM | 7.5 x 10 ⁻²⁹ | 6.3 x 10 ⁻⁸ | |
| IM + (-)-Depr / BM | 0.0 | 2.7 x 10 ⁻¹⁰ | |
| IM + (-)-Desmeth / BM | 3.4 x 10 ⁻²⁶ | 3.0 x 10 ⁻⁷ | |
| BM + (-)-Depr / BM | 0.0 | 3.5 x 10 ⁻⁷ | |
| BM + (-)-Desmeth / BM | 5.8 x 10 ⁻²¹ | 2.7 x 10 ⁻¹⁰ | |
| BM + 2.5 μ M Proad / BM | 3.3 x 10 ⁻¹ | 4.4 x 10 ⁻¹ | |
| BM + 10 μ M Proad / BM | 1.0 | 3.7 x 10 ⁻¹ | |
| BM + 25 μ M Proad / BM | 8.3 x 10 ⁻¹ | 8.8 x 10 ⁻¹ | |
| BM + 50 μ M Metyr / BM | 9.6 x 10 ⁻² | 1.1 x 10 ⁻¹ | |
| BM + 100 μ M Pip.But / BM | 1.3 x 10 ⁻² | 3.1 x 10 ⁻² | |
| BM + 2.5 μ M Proad + (-)-Depr / BM | 2.7 x 10 ⁻⁹ | 1.6 x 10 ⁻⁴ | |
| BM + 2.5 μ M Proad + (-)-Desmeth / BM | 7.8 x 10 ⁻¹¹ | 1.6 x 10 ⁻⁴ | |
| BM + 10 μ M Proad + (-)-Depr / BM | 5.3 x 10 ⁻⁴ | 4.0 x 10 ⁻³ | |
| BM + 10 μ M Proad + (-)-Desmeth / BM | 2.3 x 10 ⁻¹⁰ | 4.0 x 10 ⁻³ | |
| BM + 25 μ M Proad + (-)-Depr / BM | 4.9 x 10 ⁻¹ | 5.7 x 10 ⁻¹ | |
| BM + 25 μ M Proad + (-)-Desmeth / BM | 9.3 x 10 ⁻¹⁰ | 4.0 x 10 ⁻³ | |
| BM + 50 μ M Metyr + (-)-Depr / BM | 5.0 x 10 ⁻⁶ | 1.6 x 10 ⁻⁴ | |
| BM + 50 μ M Metyr + (-)-Desmeth / BM | 2.3 x 10 ⁻¹⁰ | 4.0 x 10 ⁻³ | |
| BM + 100 μ M Pip.But + (-)-Depr / BM | 1.0 x 10 ⁻¹ | 1.0 x 10 ⁻¹ | |
| BM + 100 μ M Pip.But + (-)-Desmeth / BM | 2.3 x 10 ⁻¹⁰ | 4.0 x 10 ⁻³ | |

Table 5. Statistical analysis of data for intact nuclear counts after methamphetamine and amphetamine treatments

| Treatment | T-test for independent samples | | Mann-Whitney U test |
|---|--------------------------------|------------------------|-----------------------|
| | Intact nuclear counts | Intact nuclear counts | Intact nuclear counts |
| BM + (-)-Meth 10 ⁻⁵ M / BM | 7.4 x 10 ⁻¹ | 1.07 | |
| BM + (-)-Meth 10 ⁻⁷ M / BM | 1.0 | 1.0 | |
| BM + (-)-Meth 10 ⁻⁹ M / BM | 3.2 x 10 ⁻¹ | 4.9 x 10 ⁻¹ | |
| BM + (-)-Meth 10 ⁻⁵ M + (-)-Depr / BM | 1.0 x 10 ⁶ | 4.0 x 10 ⁻³ | |
| BM + (-)-Meth 10 ⁻⁵ M + (-)-Desmeth / BM | 6.5 x 10 ⁵ | 2.9 x 10 ⁻² | |
| BM + (-)-Meth 10 ⁻⁷ M + (-)-Depr / BM | 5.7 x 10 ⁷ | 2.9 x 10 ⁻² | |
| BM + (-)-Meth 10 ⁻⁹ M + (-)-Depr / BM | 5.1 x 10 ⁸ | 2.9 x 10 ⁻² | |
| BM + (-)-Amph 10 ⁻³ M / BM | 2.6 x 10 ⁻¹ | 2.8 x 10 ⁻¹ | |
| BM + (-)-Amph 10 ⁻⁵ M / BM | 1.0 | 2.6 x 10 ⁻¹ | |
| BM + (-)-Amph 10 ⁻⁷ M / BM | 2.9 x 10 ⁻³ | 4.0 x 10 ⁻³ | |
| BM + (-)-Amph 10 ⁻⁹ M / BM | 2.0 x 10 ¹ | 2.8 x 10 ⁻¹ | |
| BM + (-)-Amph 10 ⁻³ M + (-)-Depr / BM | 1.5 x 10 ¹ | 5.0 x 10 ⁻¹ | |
| BM + (-)-Amph 10 ⁻⁵ M + (-)-Depr / BM | 1.0 x 10 ⁻¹ | 4.0 x 10 ⁻³ | |
| BM + (-)-Amph 10 ⁻⁵ M + (-)-Desmeth / BM | 1.7 x 10 ² | 2.8 x 10 ⁻² | |
| BM + (-)-Amph 10 ⁻⁷ M + (-)-Depr / BM | 3.0 x 10 ⁷ | 4.0 x 10 ⁻³ | |
| BM + (-)-Amph 10 ⁻⁹ M + (-)-Depr / BM | 3.0 x 10 ⁷ | 4.0 x 10 ⁻³ | |

3.8 (-) -Desmethyldeprenyl Increases the Survival of Oligodendroglial Cells by Inducing New Protein Synthesis

To determine if the increases in survival effected by (-) -desmethyldeprenyl were dependent on transcription or translation in a similar manner to that previously shown for the neuronally differentiated PC12 cells (Tatton *et al.*, 1994), the oligodendroglial cultures were treated with a transcriptional blocker, actinomycin and a translational blocker, cycloheximide. Actinomycin was used at 1, 2.5 and 5 µg / ml while cycloheximide was used at 1, 5, 10, and 50 µg/ml concentrations. Neither agent altered the numbers of intact nuclei for cells that had undergone withdrawal of IGF-I and insulin (compare the white bar in the BM group to the white bars in the BM + Cycloheximide and the BM + Actinomycin groups in figure 12). Similar to undifferentiated PC12 cells after serum withdrawal (Rukenstein *et al.*, 1991) and neuronally differentiated PC12 cells after serum and NGF withdrawal (Tatton *et al.*, 1994), this data indicates that apoptosis in the oligodendroglial cells is independent of a requirement for new protein synthesis and proceeds through signaling by constitutive proteins.

In contrast to their action on apoptosis itself, both agents reduced the capacity of 10^{-9} M (-) -desmethyldeprenyl to increase the number of the oligodendroglial cells after IGF-I and insulin withdrawal. The reduction in the capacity of (-) -desmethyldeprenyl to increase cell numbers was concentration dependent and induced a complete loss of the (-) desmethyldeprenyl induced survival at concentrations between 10 and 50 µg/ml for cycloheximide and 2.5 and 5.0 µg/ml for actinomycin D. See tables 6 and 7 for statistical probabilities.

Table 6. Statistical analysis of data for intact nuclear counts for cycloheximide treatment

| Treatment | T-test for independent samples | | Mann-Whitney U test |
|-------------------------------------|--------------------------------|-----------------------|-----------------------|
| | Intact nuclear counts | Intact nuclear counts | Intact nuclear counts |
| BM / IM | 2.5×10^{-16} | | 7.7×10^{-4} |
| BM + (-)-Desmeth / BM | 1.6×10^{-17} | | 7.7×10^{-4} |
| IM + (-)-Desmeth / BM | 3.7×10^{-17} | | 7.2×10^{-4} |
| BM + 1 μ M CHX / BM | | 7.4×10^{-1} | 8.7×10^{-1} |
| BM + 5 μ M CHX / BM | | 5.3×10^{-1} | 6.2×10^{-1} |
| BM + 10 μ M CHX / BM | | 8.0×10^{-2} | 1.1×10^{-1} |
| BM + 50 μ M CHX / BM | | 3.0×10^{-1} | 5.2×10^{-1} |
| BM + 1 μ M CHX + Desmeth. / BM | | 4.2×10^{-14} | 7.7×10^{-4} |
| BM + 5 μ M CHX + Desmeth. / BM | | 7.9×10^{-16} | 7.7×10^{-4} |
| BM + 10 μ M CHX + Desmeth. / BM | | 2.4×10^{-8} | 7.7×10^{-4} |
| BM + 50 μ M CHX + Desmeth. / BM | | 4.2×10^{-5} | 7.7×10^{-5} |

Table 7. Statistical analysis of data for intact nuclear counts for actinomycin treatment

| Treatment | T-test for independent samples | | Mann-Whitney U test Intact nuclear counts |
|-----------------------------------|--------------------------------|------------------------|--|
| | Intact nuclear counts | Intact nuclear counts | |
| BM / IM | 2.5 x 10 ⁻¹⁶ | | 7.7 x 10 ⁻⁴ |
| BM + (-)-Desmeth / BM | 1.6 x 10 ⁻¹⁷ | | 7.7 x 10 ⁻⁴ |
| IM + (-)-Desmeth / BM | 3.7 x 10 ⁻¹⁷ | | 7.2 x 10 ⁻⁴ |
| BM + 1µg/ml ACT / BM | | 1.3 x 10 ⁻¹ | 1.5 x 10 ⁻¹ |
| BM + 2.5µg/ml ACT / BM | | 7.7 x 10 ⁻¹ | 7.9 x 10 ⁻¹ |
| BM + 5µg/ml ACT / BM | | 6.0 x 10 ⁻¹ | 5.2 x 10 ⁻¹ |
| BM + 1µg/ml ACT + Desmeth. / BM | 4.0 x 10 ⁻¹⁷ | | 7.7 x 10 ⁻⁴ |
| BM + 2.5µg/ml ACT + Desmeth. / BM | 3.6 x 10 ⁻⁴ | | 3.2 x 10 ⁻³ |
| BM + 5µg/ml ACT + Desmeth. / BM | 3.9 x 10 ⁻³ | | 1.1 x 10 ⁻² |

Those concentrations are within the range that reduces new protein synthesis to 10% or less in other cell culture systems (see (Rukenstein *et al.*, 1991; Tatton *et al.*, 1994)). Accordingly, (-)-desmethyldeprenyl appears to require new protein synthesis to reduce apoptosis caused by IGF-I and insulin withdrawal in oligodendroglial cells. The interpretation of a need for new protein synthesis is strengthened by the finding that both a translational and a transcriptional inhibitor block the increased survival induced by desmethyldeprenyl.

3.9 Mitochondrial Membrane Potential In Oligodendroglial Apoptosis

Studies in primary cultures of cerebellar neurons (Paterson *et al.*, 1998) and in neuronally differentiated PC12 cells (Wadia *et al.*, 1998) have shown that (-)-deprenyl prevents the decrease in $\Delta\Psi_M$ that occurs early in many forms of apoptosis and results in opening of the PTP (see details above). Measurements of mitochondrial CMTMR fluorescence intensities imaged with laser confocal microscopy were used to estimate the $\Delta\Psi_M$ in the oligodendroglial cells. CMTMR has been compared to other mitochondrial potentiometric dyes and has been shown to offer a reliable estimate of $\Delta\Psi_M$ in individual mitochondria *in situ* (see (Wadia *et al.*, 1998)). $\Delta\Psi_M$ was measured at 18 hours after washing, the time point at which maximum numbers of apoptotic nuclei were found to be present in the oligodendroglial cells (see above).

The distributions of mitochondrial CMTMR fluorescence for PROLs, OLs and ASTs in IM indicated that OL and PROL mitochondria have significantly higher levels of $\Delta\Psi_M$ than AST mitochondria (see the upper row of distributions in figure 13, typical

CMTMR laser confocal microscope images for each type under the corresponding treatment conditions are superimposed on each distribution in figures 13-16). The shape of the distributions indicates that OLs and PROLs have a high proportion of mitochondria with relatively high level $\Delta\Psi_M$. Withdrawal of IGF-I and insulin shifted with mitochondrial CMTMR distributions to significantly lower values for the ASTs, PROLs and OLs (see the lower row of distributions in figure 13). The relative decreases were particularly marked for the PROL and OL mitochondria. These finding indicate that apoptosis induced in PROLs and OLs by IGF-I and insulin withdrawal involves a decrease in $\Delta\Psi_M$ and likely is mitochondrially dependent apoptosis (see above).

Treatment with 10^{-9} M (-) -deprenyl (see the upper row of distributions in figure 14) and 10^{-9} M (-) -desmethyldeprenyl (see the lower row of distributions in figure 14) shifted the CMTMR fluorescence distributions for mitochondria in ASTs, PROLs and OLs to levels that were not significantly different to those found for IM (see Table 8). Similar to cultured cerebellar neurons (Paterson *et al.*, 1998) and neuronally differentiated PC12 cells (Paterson *et al.*, 1998), (-)-deprenyl prevented the decreases in PROLs and OLs which may account for its capacity to reduce apoptosis in the cells. This is the first study to show that (-)-desmethyldeprenyl shares the capacity of (-)-deprenyl to maintain $\Delta\Psi_M$ in cells that have sustained an insult that leads to apoptosis, in this case IGF-I and insulin withdrawal.

Experiments in which proadifen ($10\mu M$), metyrapone ($50\mu M$) or piperonyl butoxide ($100\mu M$) were added to IGF-I/insulin withdrawn cells that were treated with $10^{-9} M$ (-)-deprenyl showed that prevention of (-)-deprenyl metabolism by cytochrome P450 inhibition blocked the increases in $\Delta\Psi_M$ induced by (-)-deprenyl on OL mitochondria (see the upper row of distributions in figure 15). Similar experiments using the three P450 inhibitors with (-)-desmethyldeprenyl, rather than (-)-deprenyl, showed prevention of (-)-deprenyl metabolism did not compromise the capacity of (-)-desmethyldeprenyl to maintain $\Delta\Psi_M$ in OL mitochondria after IGF-I/insulin withdrawal (see the lower row of distributions in figure 15). These findings appear to correspond to those above in which the three P450 inhibitors blocked the capacity of (-)-deprenyl to increase oligodendroglial survival but did not affect the capacity of (-)-desmethyldeprenyl to increase the survival.

In a final series of experiments, CMTMR mitochondrial fluorescence was measured in IGF-I /insulin withdrawn OL mitochondria treated with $10^{-9} M$ (-)-deprenyl in combination with $10^{-5} M$ (-)-methamphetamine or $10^{-5} M$ (-)-amphetamine (see upper row of distributions in figure 16). Similar experiments were carried out with $10^{-9} M$ (-)-desmethyldeprenyl rather than (-)-deprenyl (see lower row of distributions in figure 16). These data show that (-)-methamphetamine and (-)-amphetamine competition reduce the capacity of (-)-deprenyl and (-)-desmethyldeprenyl to maintain $\Delta\Psi_M$ in OL mitochondria after IGF-I and insulin withdrawal. These findings appear to correspond to the findings presented above showing that (-)-methamphetamine and (-)-amphetamine competition reduces the capacity of (-)-deprenyl and (-)-desmethyldeprenyl to increase

the survival of oligodendroglial cells after IGF-I and insulin withdrawal.

Table 8. Statistical testing of data for the mitochondrial membrane potential ($\Delta\Psi_M$) of oligodendroglial cells

| Treatment | Mann - Whitney U Test | | | T - test for independent samples | | |
|----------------------|---------------------------|---------------------------|---------------------------|----------------------------------|---------------------------|---------------------------|
| | AST | PROL | OL | Treatment | AST | PROL |
| BM / IM | >1.00 x 10 ⁻¹⁵ | >1.00 x 10 ⁻¹⁵ | >1.00 x 10 ⁻¹⁵ | BM / IM | >1.00 x 10 ⁻¹⁵ | >1.00 x 10 ⁻¹⁵ |
| BM-D9 / BM | >1.00 x 10 ⁻¹⁵ | >1.00 x 10 ⁻¹⁵ | >1.00 x 10 ⁻¹⁵ | BM-D9 / BM | >1.00 x 10 ⁻¹⁵ | >1.00 x 10 ⁻¹⁵ |
| BM-D9 / IM | 4.4 x 10 ⁻⁵ | 2.6 x 10 ⁻⁷ | 8.8 x 10 ⁻⁵ | BM-D9 / IM | 4.9 x 10 ⁻⁵ | 2.0 x 10 ⁻⁷ |
| BM-DS9 / BM | >1.00 x 10 ⁻¹⁵ | >1.00 x 10 ⁻¹⁵ | >1.00 x 10 ⁻¹⁵ | BM-DS9 / BM | >1.00 x 10 ⁻¹⁵ | >1.00 x 10 ⁻¹⁵ |
| BM-DS9 / IM | >1.00 x 10 ⁻¹⁵ | 1.1 x 10 ⁻³ | 8.8 x 10 ⁻¹⁴ | BM-DS9 / IM | >1.0 x 10 ⁻¹⁵ | 1.8 x 10 ⁻² |
| BM-D9 + Proad. / BM | — | — | 4.23 x 10 ⁻¹³ | BM-D9 + Proad. / BM | — | 1.2 x 10 ⁻¹⁰ |
| BM-DS9 + Proad. / BM | — | — | >1.00 x 10 ⁻¹⁵ | BM-DS9 + Proad. / BM | — | >1.00 x 10 ⁻¹⁵ |
| BM-D9 + Meta. / BM | — | — | 2.9 x 10 ⁻¹¹ | BM-D9 + Meta. / BM | — | 7.7 x 10 ⁻¹¹ |
| BM-DS9 + Meta. / BM | — | — | >1.00 x 10 ⁻¹⁵ | BM-DS9 + Meta. / BM | — | >1.00 x 10 ⁻¹⁵ |
| BM-D9 + P. But / BM | — | — | 4.8 x 10 ⁻¹⁴ | BM-D9 + P. But / BM | — | 9.5 x 10 ⁻¹¹ |
| BM-DS9 + P. But / BM | — | — | >1.00 x 10 ⁻¹⁵ | BM-DS9 + P. But / BM | — | >1.00 x 10 ⁻¹⁵ |
| BM-D9 + MA. / BM | — | — | 3.6 x 10 ⁻⁴ | BM-D9 + MA. / BM | — | 3.7 x 10 ⁻⁵ |
| BM-DS9 + MA. / BM | — | — | 6.4 x 10 ⁻¹ | BM-DS9 + MA. / BM | — | 1.0 x 10 ⁻¹ |
| BM-D9 + AM / BM | — | — | 2.0 x 10 ⁻¹ | BM-D9 + AM / BM | — | 2.0 x 10 ⁻¹ |
| BM-DS9 + AM / BM | — | — | 1.3 x 10 ⁻¹ | BM-DS9 + AM / BM | — | 4.7 x 10 ⁻¹ |

4.0 Discussion

4.1 An *In Vitro* Model System

This thesis describes a primary culture model established to study the death of PROLs and OLs after IGF-I and insulin withdrawal. There are certain advantages to the use of glial primary cultures. First, the purity of the cell populations derived from the primary mixed glial cultures is considerably higher when compared to the cell populations obtained from explants or reaggregate cultures. Second, mixed glial primary cultures offer the advantage of the presence of a stratified layer of O-2A progenitor cells over an astrocytic cell layer therefore purified populations of oligodendrocytes or astrocytes can be obtained from the same culture using a replating procedure.

O-2A progenitors can be isolated from the underlying astrocytic layer using mechanical shake-off method, by immunoisolation on solid substrates, or by fluorescence activated cell sorting. The isolated progenitors can be then developmentally synchronized to obtain cells at specific phenotypic stages. The use of primary cultures allows for the control of the microenvironment in which the primary cultured cells grow. Defined culture conditions facilitate the developmental synchronization of the O-2A progenitor differentiation. In addition, a controlled culture environment facilitates the identification and testing of the effects of trophic factors or other agents on oligodendroglial differentiation or survival.

An important finding of the studies utilizing *in vitro* models is that oligodendroglial cells in culture follow a schedule that approximates the timing of differentiation of the progenitor cells *in vivo* (Gard and Pfeiffer, 1989). Oligodendroglial cells are formed at birth and differentiate postnatally as opposed to neurons, which

become established during embryogenesis. It is interesting to note that oligodendrocytes develop later than neuronal cells after the completion of axonal outgrowth. This late development has been postulated to occur because oligodendrocytes exert a strong inhibitory effect on axonal growth (Caroni and Schwab, 1988).

The cerebral O-2A progenitor cells were first identified in a rat optic nerve model (Raff *et al.*, 1983). The current study has utilized O-2A progenitor cells isolated from the cerebral cortices of the rat in its *in vitro* model system. Several other studies have used the rat cerebral cortex as a source for isolating O-2A progenitor cells instead of the optic nerve (Behar *et al.*, 1988; Espinosa de los Monteros *et al.*, 1988; Espinosa de los Monteros *et al.*, 1986; McMorris *et al.*, 1986). The use of the cerebral cortex offers the advantage of obtaining a higher yield of O-2A progenitor cells in comparison to the optic nerve.

4.2 Immunocytochemical and Morphological Cell Identification

The identification of oligodendroglial cell types on the sole basis of immunocytochemical data is not always practical by itself. This can be illustrated by using the example of the cell stage specific expression of a surface antigen, galactocerebroside (GC). Many earlier studies incorrectly interpreted the expression of GC to be linked to terminal differentiation and maturation of oligodendroglial cells. As the O-2A progenitor cells differentiate into the partially differentiated PROLs, the cells lose their reactivity to A2B5 and begin to express the surface antigen GC and an intracellular antigen, CNPase-I. Therefore, the expression of GC coincides with the appearance of PROLs rather than the OLs. The PROLs mature to form the fully

differentiated OLs. Previous studies have shown that that cells at this final stage of differentiation express MBP and PLP. Additionally, the differentiated cells also continue to express the PROL markers, GC and CNPase-I. Since there is a considerable overlap in the expression of antigens in the partially differentiated and fully differentiated oligodendroglial cells, it is necessary to combine the immunocytochemical observations with morphological features of these cells to correctly identify of the cell types found in the oligodendroglial lineage.

In the present study, positive identification of the individual cell types in the cultures was achieved using a combination of approaches including phase contrast microscopy, immunocytochemistry and methylene blue morphological staining. The PROLs were found to express GC and CNPase-I and had three to four primary processes with few secondary processes. The fully differentiated OLs however were seen to possess six to eight primary processes and numerous web-like secondary and tertiary processes and also were immunopositive for antibodies that recognized MBP and PLP. The identification of MBP and PLP immunopositive cells as fully differentiated cells of the oligodendroglial lineage gains support from several studies which have observed that the MBP positive cells are incapable of any further cell division (Wood and Bunge, 1986).

The correlation of the presence of immunocytochemical marker proteins to specific morphological changes in the cells, particularly changes in process morphology, allowed for the counting of changes in the numbers of specific cell types at a number of time points after IGF-I and insulin withdrawal using a simple methylene blue staining process. Because of cell to cell variability in immunoreaction product, dependence on immunocytochemistry alone would have made the procedure considerably less reliable.

4.3 Insulin and IGF-I and Oligodendroglial Proliferation and Differentiation

Insulin and IGF-I are structurally and functionally related polypeptides that regulate a number of cellular processes like proliferation, differentiation and survival. The CNS was thought to be insulin and IGF-I independent since serum insulin and IGF-I do not cross the blood-brain barrier. However, the findings of the presence of insulin and insulin receptors in the rat brain radically changed the view that the CNS was insulin independent (Baskin *et al.*, 1983; Havrankova *et al.*, 1978; Kappy *et al.*, 1984). It is now known that IGF-I and II, their receptors, and IGF binding proteins (IGFBPs; secreted proteins that modulate IGF actions) are expressed early in CNS development (Baxter, 1991). So far six IGFBPs (IGFBP-1 through 6) have been identified. The IGFBPs have been suggested to augment the binding of IGF-I to its cell surface receptors. Binding sites for IGF-I have now been identified in virtually all brain regions of the adult rat brain using quantitative autoradiographic techniques (Bohannon *et al.*, 1988).

IGF-I is synthesized in the subventricular zone of the brain by type-1 astrocytes (Ballotti *et al.*, 1987; Bartlett *et al.*, 1991; Rotwein *et al.*, 1988). *In situ* hybridization studies have determined that, in the CNS of the rat, IGF-I expression begins by embryonic day 14 (Bartlett *et al.*, 1991) with peak expression of IGF-I occurring postnatally (Rotwein *et al.*, 1988; Werner *et al.*, 1989). The expression pattern of IGF system proteins during brain growth suggests highly regulated and developmentally timed IGF actions on specific populations of neurons. Apart from influencing neuronal development, IGF-I is also critical to oligodendroglial proliferation and differentiation.

In vitro, IGF-I has been shown to stimulate the proliferation of neuron progenitors and/or the survival of neurons and oligodendrocytes, and in some cultured neurons, to

stimulate functions like neurite outgrowth and differentiation. McMorris and co-workers (McMorris *et al.*, 1986) found that physiological concentrations of insulin and IGF-I induced the proliferation of O-2A progenitor cells. The proliferative effect of IGF-I on the O-2A progenitor cells was demonstrated by using tritiated thymidine incorporation of newly synthesized DNA as a marker of oligodendrocyte proliferation *in vitro* (McMorris and Dubois Dalcq, 1988). The same study also observed decreased tritiated thymidine labeling when cells were grown for two weeks or longer suggesting that IGF-I is not mitogenic to the O-2A lineage cells upon their differentiation into oligodendrocytes. It seems likely that both insulin and IGF-I together influence O-2A cell proliferation. This developmental feature gains indirect support from the evidence that both insulin (IR) and IGF receptor (IGFR) mRNAs have been found in O-2A progenitor cells (Han *et al.*, 1987; Shemer *et al.*, 1987; Van Schravendijk *et al.*, 1984). The insulin receptor mRNA levels found in O-2A progenitor cells is about 30 times more than that found in astrocytes or in neuronal cells (Baron Van Evercooren *et al.*, 1991). Accordingly, the facilitation of O-2A cell proliferation by insulin and IGF-I likely accounts for high proportion of O-2A cells found at day 12 in the *in vitro* model developed in the present thesis work.

Insulin and/or IGF-I act as a differentiation factor for the O-2A progenitor cells. The biological effects of insulin and IGF-I on oligodendroglial differentiation are triggered by the specific binding of these molecules to IR and IGFR (Mozell and McMorris, 1991). Receptor blocking experiments have revealed that the relative potency of induction of oligodendrocyte development depends on the binding affinity to IGFRs (McMorris *et al.*, 1986). The beta subunit of both IR and IGFR consists of a transmembrane polypeptide chain, which contains a highly conserved catalytic tyrosine

kinase domain. Within a few seconds of the binding of insulin and IGF-I to its receptors, the tyrosines undergo rapid phosphorylation. This subsequently leads to the phosphorylation of several intracellular substrates like Ras, Raf and phosphoinositol- 3- kinase (PI-3 kinase) which eventually induce oligodendroglial proliferation and subsequent differentiation into the mature oligodendroglia.

The occurrence of IGF-I mRNA in both the gray and white matter areas of the developing rat brain indicated that developing oligodendrocytes might themselves be synthesizing IGF-I for their subsequent maturation (Rotwein *et al.*, 1988). This finding suggests that differentiation of oligodendrocyte precursors is not only regulated by the IGF-I produced by the type-1 astrocytes but also by the release of IGF-I in an autoregulatory manner. The influence of insulin and IGF-I on O-2A differentiation likely contributed to the rapid increase the number of PROLs and OLs between 12 and 16 DIV found in the present *in vitro* model.

Insulin and IGF-I are considered to be involved in the regulation of myelin gene expression and myelin synthesis. In the present study, data obtained suggests that insulin and IGF-I regulate PROL and OL specific proteins like GC, CNPase-I, MBP and PLP. The western blot data presented in the present study showed a decrease in MBP, GC and CNPase I in the oligodendroglial cells after IGF-I and insulin withdrawal. Although part of the decrease can likely be accounted for by the greater proportion of death of PROLs and OLs than other cell types in the cultures, part of the decrease may result from decreased synthesis of the three proteins caused by the withdrawal of IGF-I and insulin.

Little is known about the functional roles of the four PROL and OL proteins. MBP and PLP together form 80% of the total myelin in the CNS. There have been recent

reports on the involvement of PLP in mediating the survival of oligodendrocytes. In mice carrying mutations of PLP, there is a dramatic decrease in the numbers of oligodendrocytes as well as aberrant myelin formation (Jackson and Duncan, 1988). This suggests that PLP is crucial for the survival and myelinating capabilities of oligodendroglial cells.

Paradoxically, other studies have offered evidence that overexpression of the PLP gene leads to OL cell death (Kagawa *et al.*, 1994). A very recent study has demonstrated that the perinuclear accumulation of PLP leads to the apoptotic death of OLs in a mice model of Pelizaeus-Merzbacher disease, a demyelinating disease occurring due to mutations, deletions or duplications of the PLP gene (Gow *et al.*, 1998). The findings of all these studies suggest that PLP may play a role in regulating OL survival.

4.4 Insulin, IGF-I and Oligodendroglial Apoptosis

The *in vitro* model system of the present study demonstrates that insulin and IGF-I serve to decrease apoptosis in O-2A progenitors, PROLs and OLs. Studies with oligodendrocytes in the rat optic nerve have revealed that oligodendroglial cells are overproduced during development (Barres *et al.*, 1992). Over half of the newly formed oligodendrocyte progenitor cells die due to lack of available trophic signals. Based on their findings, Barres and co-workers hypothesized that survival / trophic factors ultimately decide the final numbers of myelin forming oligodendrocytes in any specific region of the CNS. Insulin and IGF-I, not only affect oligodendroglial differentiation and maturation but also contribute to the regulation of oligodendroglial cell survival (McMorris *et al.*, 1993).

It was previously shown that IGF-I and insulin decrease apoptosis in O-2A progenitors which was thought to be the point of regulation of OL numbers (Barres *et al.*, 1992). Data from the present study is the first to show that insulin and IGF-I can also decrease apoptosis of PROLs and OLs. These findings are consistent with previous studies showing that insulin can increase the numbers of oligodendrocytes grown in serum free conditions (Eccleston and Silberberg, 1984; Saneto and de Vellis, 1985). Other studies have shown that IGF-I produced by developing oligodendrocytes or astrocytes, acts additively with trophic factors like PDGF and NT-3 to promote the proliferation and survival of oligodendrocyte precursor cells (Barres *et al.*, 1993). The present study suggests that similar actions may extend to fully differentiated OLs themselves and those actions may depend on an anti-apoptotic capacity of IGF-I and insulin on the OLs.

Very few studies have focused on glial cell apoptosis, more particularly on PROL and OL apoptosis. The first report showing a possible relationship between trophic factor withdrawal and an O-2A lineage cell apoptosis came from the studies of Barres and colleagues (Barres *et al.*, 1992). Their study demonstrated that newly formed oligodendroglial precursors die with morphological features suggestive of apoptosis when deprived of trophic support. Another study demonstrated that oligodendroglial progenitor cells isolated from the rat forebrain showed apoptotic cell death features upon removal of bFGF (Yasuda *et al.*, 1995). The results of the present study show that differentiated cells of the oligodendroglial lineage like the PROLs and the OLs die by apoptosis upon withdrawal of insulin and IGF-I. The presence of a combination of trophic factors may be essential to prevent oligodendroglial cell apoptosis *in vivo*.

The insulin and IGF-I withdrawn oligodendroglial cells showed evidence for apoptotic nuclear degradation within 6 hours after IGF-I and insulin withdrawal. Peak apoptotic death was observed at 18 hours after withdrawal of insulin and IGF-I. The time course of apoptosis observed in the present study is similar to that of IGF-I deprived rat optic nerve O-2A progenitor cells which die within 18 hours (Barres *et al.*, 1992). Based upon those findings, it seems likely that after withdrawal of insulin and IGF-I, both undifferentiated O-2A progenitor cells and differentiated PROLs and OLs undergo apoptosis with a similar time course of death. However, the present studies suggested that IGF-I/insulin withdrawal induced apoptotic death seems to be higher in the more differentiated cells of the oligodendroglial lineage.

The time course of apoptotic cell death can vary depending on the cell type and the insult that induces apoptosis. Apoptosis in neuronally differentiated PC12 cells has been seen to begin between 6 and 12 hours after serum and NGF withdrawal (Wadia *et al.*, 1998). The apoptotic death of insulin and IGF-I deprived oligodendroglial cells appears to occur over a more protracted time course than that of the serum and NGF deprived PC12 cells. The time course of apoptosis seems to depend on the intensity of the insult that induces the apoptosis (Hartley *et al.*, 1994), which may account for the longer time course of the oligodendroglial apoptosis induced by IGF-I and insulin withdrawal.

4.5 Cell Density and Apoptosis

Although it is known that the absence of trophic factors, insulin and IGF-I decreases the survival of oligodendroglial cells, it is not known whether extrinsic factors like cell plating density regulates oligodendroglial apoptosis. The present study demonstrates that oligodendroglial cells underwent apoptosis, which was at least in part, mediated by cell plating density. At lower plating density, the number of apoptotic nuclei was approximately 15 fold higher in BM as opposed to IM. Higher plating density however increased the number of apoptotic nuclei in BM approximately 8.5 fold higher than in IM. This data suggests that oligodendroglial cells at lower plating density are more vulnerable to apoptosis induced by trophic withdrawal.

Lower plating densities have been shown to cause apoptotic cell death in several cell types. Lens epithelial cells, rat and chick chondrocytes, HL-60 cells, sciatic nerve fibroblasts and neutrophils die by apoptosis when cultured in low plating densities in the absence of serum or growth factors (Ishizaki *et al.*, 1994; Ishizaki *et al.*, 1995). A number of possibilities emerge that could account for the decreased survival and increased apoptosis when cells are cultured at lower plating densities. First, it seems likely that an absence of extracellular survival promoting signals can decrease cell survival. Secondly, at lower plating densities there might be a decrease in the levels of antioxidant molecules which would thereby facilitate the intracellular build up of oxidative radicals that can cause cell death by apoptosis. Lastly, lower plating densities might induce the release of apoptosis-initiating factor by a mechanism that would involve the activation of ICE like proteases, as described earlier. The released apoptosis initiating factors can induce apoptotic DNA fragmentation.

4.6 New Protein Synthesis and OL and PROL Apoptosis

As shown for the first time by the above studies using actinomycin D and cycloheximide, in a similar manner to the PC12 cell apoptosis caused by serum (Rukenstein *et al.*, 1991) or serum and NGF withdrawal (Tatton *et al.*, 1994), oligodendroglial apoptosis induced by IGF-I and insulin withdrawal is new protein synthesis independent. Those findings contrast with an earlier report that cycloheximide and actinomycin D inhibit the cell death of O-2A progenitor cells (Barres *et al.*, 1992). The study of Barres and colleagues (Barres *et al.*, 1992) hypothesized that oligodendroglial cells possess a suicide program which is activated when cells are deprived of essential trophic support. It is possible that newly formed oligodendroglial precursor cells, which were examined in that study, require the synthesis of "death" proteins to complete the apoptotic process. However, further differentiation into PROLs and OLs may result in a modification of the apoptotic process so that newly synthesized proteins are not required and the process depends on constitutive proteins.

4.7 (-)-Deprenyl and Increased Oligodendroglial Survival

The present study showed that (-)-deprenyl increased the survival of oligodendroglial cells which were deprived of insulin and IGF-I. The anti-apoptotic action of deprenyl seems to be limited to its (-) enantiomer (Ansari *et al.*, 1993) as has been shown for oligodendroglial cells in the present studies. (-)-Deprenyl inhibits MAO-B by forming a non-covalent complex leading to the oxidation of (-)-deprenyl and reduction of the flavine adenine dinucleotide (FAD) moiety. (-)-Deprenyl and the reduced FAD moiety bind covalently. Since MAO-B possesses FAD binding domains,

(-) -deprenyl in combination with reduced FAD binds to the enzyme and inactivates it.

However, as discussed above, (-) -deprenyl mediates its survival enhancing action in an MAO-B independent manner. Recent work has suggested that (-)-deprenyl-like compounds may reduce apoptosis by binding to glyceraldehyde-3-phosphate dehydrogenase (GAPDH) (Kragten *et al.*, 1998). Although GAPDH facilitates apoptosis in a variety of types of neurons (Ishitani and Chuang, 1996; Ishitani *et al.*, 1996; Ishitani *et al.*, 1996; Ishitani *et al.*, 1997; Sunaga *et al.*, 1995), it is not known whether it plays a role in oligodendroglial apoptosis.

The finding that (-)-deprenyl reduces oligodendroglial apoptosis suggest a possible role for GAPDH in that apoptosis, if in fact, binding to GAPDH mediates (-)-deprenyl anti-apoptosis. The P450 cytochrome blockade experiments in present work are the first to establish that (-)-desmethyldeprenyl rather than (-)-deprenyl itself mediates the anti-apoptosis in the oligodendroglial cells. Experiments with three different general P450 cytochrome inhibitors, proadifen (SKF 525A), piperonyl butoxide and metapyrone, all led to the same findings: 1) that prevention of (-)-deprenyl metabolism by P450 cytochromes blocks the capacity of the compound to reduce oligodendroglial apoptosis and 2) prevention of the metabolism of (-)-desmethyldeprenyl by P450 cytochromes does impair the capacity of (-)-desmethyldeprenyl to reduce oligodendroglial apoptosis. Three P450 cytochrome inhibitors were required since most of the inhibitors have several sites of action. For example, proadifen and metapyrone inhibit P450 cytochromes and both also modulate bradykinin-releasable Ca^{2+} -pumping pools in cells (Graber *et al.*, 1997; Suarez-Kurtz and Bianchi, 1970). Modulation of the Ca^{2+} pools might be argued to be responsible for the blockade of anti-apoptosis by (-)-deprenyl rather than P450

cytochrome inhibition. Piperonyl butoxide also inhibits P450 cytochromes but does not share the Ca^{2+} action of the other two inhibitors (Benchaoui and McKellar, 1996). Accordingly, the use of three different inhibitors greatly strengthens the interpretation that cytochrome P450 mediated metabolism of (-)-deprenyl is necessary for its anti-apoptotic action. Since (-)-desmethyldeprenyl appears to be the active compound, it might bind to GAPDH, rather than (-)-deprenyl, and the binding may compromise the pro-apoptotic capacity of GAPDH, thereby reducing apoptosis in the oligodendroglial cells. It is possible that (+)-desmethyldeprenyl may not bind to the protein, which would account for the stereospecificity of the anti-apoptotic action on the oligodendroglial cells.

The anti-apoptotic effects of (-)-deprenyl on neuronally differentiated PC12 cells has been attributed to a capacity to alter gene transcription and induce selective changes in new protein synthesis (Tatton and Chalmers Redman, 1996). It is likely that similar changes in new protein synthesis are induced in the oligodendroglial cells, given the above findings which show that transcriptional or translational inhibition prevents either (-)-deprenyl or (-) desmethyldeprenyl from reducing oligodendroglial apoptosis.

As detailed above, (-)-deprenyl treatment induces changes in the levels of a large number of proteins in different cell types, including increases in BCL-2 (Tatton *et al.*, 1994). BCL-2 has been shown to be located, in part, in the outer membranes of mitochondria (Lithgow *et al.*, 1994; Riparbelli *et al.*, 1995), near to or at the peripheral benzodiazepine binding protein of the PTP (Carayon *et al.*, 1996). Kroemer and colleagues have shown that the presence of BCL-2 near the PTP serves to maintain PTP closure and maintain $\Delta\Psi_M$ (Marchetti *et al.*, 1996; Zamzami *et al.*, 1996). In early apoptosis, BCL-2 decreases in the mitochondrial membranes (Gillardon *et al.*, 1995), which results in PTP

opening and likely contributes to the early apoptotic decrease in $\Delta\Psi_M$. Opening of the PTP, associated with the decrease in $\Delta\Psi_M$, results in the free exchange of solutes between the mitochondrial matrix and the cytosol, mitochondrial swelling and the escape of mitochondrial factors which induce the degradative phase of apoptosis (see (Kroemer *et al.*, 1997)). Mitochondrial BCL-2 has been shown to prevent the release of pro-apoptotic factors from mitochondria (Susin *et al.*, 1996; Yang *et al.*, 1997). Agents which maintain or increase cellular levels of BCL-2, like (-)-deprenyl, would therefore be expected to maintain $\Delta\Psi_M$ and prevent opening of the PTP leading to apoptotic degradation (see (Wadia *et al.*, 1998)).

GAPDH appears to promote apoptosis by down regulation of the increase in BCL-2 synthesis that accompanies cellular damage (Carlile, Chalmers-Redman, Borden and Tatton, personal communication). The above finding that (-)-deprenyl and (-)-desmethyldeprenyl maintain $\Delta\Psi_M$ in the oligodendroglial cells could be explained by the binding of (-)-desmethyldeprenyl to GAPDH leading to a maintenance of $\Delta\Psi_M$ with maintained closure of the PTP. Prevention of PTP opening would then result in a decrease in apoptosis in the cells. The validity of this model for the action of (-)-desmethyldeprenyl will have to be evaluated in a step by step manner in the oligodendroglial cells.

Rather than acting directly on the oligodendroglial cells to increase BCL-2 levels, (-)-desmethyldeprenyl may act through astroglial intermediaries. (-)-Deprenyl has been shown to increase the synthesis of CNTF, NGF and bFGF in astrocytes (Biagini *et al.*, 1994; Semkova *et al.*, 1996; Seniuk *et al.*, 1994). It has been suggested that increased

availability of trophic support may account for the anti-apoptotic capacity of (-)-deprenyl (Koutsilieri *et al.*, 1996). A trophic basis for the decreased apoptosis could also explain the maintenance of $\Delta\Psi_M$ in the oligodendroglial cells since some trophic factors have been shown to increase $\Delta\Psi_M$ (Mattson *et al.*, 1993).

The present understanding of apoptosis is thought to be associated with a sequence of mitochondrial events involving opening of the PTP and a decrease in $\Delta\Psi_M$. Although the studies of Wadia and colleagues (Wadia *et al.*, 1998) as well as Paterson and co-workers (Paterson *et al.*, 1998) make direct measurements of mitochondria to demonstrate a fall in the $\Delta\Psi_M$ in early apoptosis, it might be argued, though, that the decrease in $\Delta\Psi_M$ is simply a correlate of apoptotic death, but is not one of the steps leading to the death. As shown in my studies, the level of cell survival and $\Delta\Psi_M$ covary across a number of different treatments. That is, as shown in table 9, factors which increase or decrease survival have the same effect on $\Delta\Psi_M$. These findings strengthen the argument that decreases in $\Delta\Psi_M$ play a role in the genesis of oligodendroglial apoptosis.

Table 9. Relationship between $\Delta\Psi_M$ and OL cell survival.

| | Survival (24 h) | $\Delta\Psi_M$ (18 h) |
|-----------------|-----------------|-----------------------|
| IM | ++++ | ++++ |
| BM | ++ | ++ |
| BM-D9 | ++++ | +++ |
| BM-Ds9 | ++++ | ++++ |
| BM-D9 + Proad. | ++ | ++ |
| BM-D9 + Meta. | ++ | ++ |
| BM-D9 + P.But. | ++ | ++ |
| BM-Ds9 + Proad. | ++++ | ++++ |
| BM-Ds9 + Meta. | ++++ | ++++ |
| BM-Ds9 + P.But. | ++++ | ++++ |
| BM-D9 + MA | ++ | + |
| BM-D9 + AM | ++ | + |
| BM-Ds9 + MA | ++ | + |
| BM-Ds9 + AM | + | + |

++++ = Control Levels

+++ = 60-90% of Control

++ = 30-60% of Control

+ = 0-30% of Control

4.8 Possible Therapeutic Benefits

Given recent evidence that OL apoptosis plays a role in the pathogenesis of MS (see introduction section above), agents like (-)-desmethyldeprenyl that reduce oligodendroglial apoptosis may be of value in slowing the time course of MS and reducing the severity of the neurological deficits associated with the disease.

5.0 Summary

The data presented in this thesis describes a primary culture model established to study glial cell apoptosis and the capacity of (-)-deprenyl and its metabolites to reduce apoptotic death. It is known that the differentiated cells of the O-2A lineage, PROLs and OLs are targets of degeneration and death in demyelinating diseases of the CNS. This primary culture model allows for the study of the cell death process in differentiated PROLs and OLs as opposed to other models, which have largely used O-2A progenitors. The study uses a number of measures to demonstrate the relationship between cellular loss and apoptotic nuclear degeneration apoptosis of differentiated PROLs and OLs upon withdrawal of insulin and IGF-I. Specifically, apoptotic death was confirmed by using two independent *in situ* methods as well as DNA gel electrophoresis. Peak apoptotic cell death for OLs and PROLs was found to occur at 18h after withdrawal of IGF-I and insulin. Cell death was also appeared to vary depending on the plating density of the cultures.

Apoptosis of the IGF-I and insulin withdrawn PROLs and OLs was significantly reduced by (-) -deprenyl. The (+) enantiomer of deprenyl did not reduce PROL and OL death showing that the actions of deprenyl is stereospecific. (-) -Deprenyl could reduce death of all the cell types of the O-2A lineage, but most particularly PROLs and OLs. This study demonstrated that a major metabolite of deprenyl, (-)-desmethyldeprenyl was also effective in reducing PROL and OL apoptosis. Blockade of cytochrome P450 enzyme dependent metabolism of (-)-deprenyl but not of (-)-desmethyldeprenyl, established that (-)-desmethyldeprenyl was the active metabolite

responsible for the anti-apoptotic effects of (-)-deprenyl. The other two major metabolites of (-)-deprenyl, (-)-methamphetamine and (-)-amphetamine did not improve cell survival after IGF-I and insulin withdrawal but competitively inhibited the anti-apoptotic actions of (-)-deprenyl or (-)-desmethyldeprenyl. The anti-apoptotic effects of (-)-desmethyldeprenyl was found to be blocked by cycloheximide and actinomycin D showing that (-)-desmethyldeprenyl was dependent on the induction of new protein synthesis for its anti-apoptotic action. Furthermore, Western blot analysis of protein levels revealed that insulin and IGF-I withdrawal decreased the levels of PROL proteins like CNP, GC and MBP but not of PLP.

The present study demonstrated that withdrawal of IGF-I and insulin shifted the mitochondrial CMTMR fluorescence intensity distributions to lower values, which represented decreases in $\Delta\Psi_M$ in the OLs, PROLs and ASTs. (-)-Deprenyl and its major metabolite (-)-desmethyldeprenyl prevented the shift of the distributions to lower values. Furthermore, experiments with cytochrome P450 inhibitors showed that the effects of (-)-deprenyl on $\Delta\Psi_M$ could be blocked but not that of (-)-desmethyldeprenyl. The other metabolites of (-)-deprenyl, (-)-methamphetamine and (-)-amphetamine, at high concentrations, shifted the mitochondrial fluorescence distributions to lower values showing a blockade of the effects of both (-)-deprenyl and (-)-desmethyldeprenyl on $\Delta\Psi_M$. These results suggest that mitochondria participate in IGF-I and insulin withdrawal induced apoptosis of OLs and PROLs, and that maintenance of $\Delta\Psi_M$ is critical to the survival of the differentiated PROLs and OLs.

6.0 References

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EQUIVALENTS

Those skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, numerous equivalents to the specific procedures described herein. Such equivalents are considered to be within the scope of the present invention and are covered by
5 the following claims. The contents of all references, issued patents, and published patent applications cited throughout this application are hereby incorporated by reference. The appropriate components, processes, and methods of those patents, applications and other documents may be selected for the present invention and embodiments thereof.

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